

Tungsten Cemented Carbide

Comprehensive Exploration of Physical & Chemical Properties, Processes, & Applications (VII)

中钨智造科技有限公司

CTIA GROUP LTD

CTIA GROUP LTD

Global Leader in Intelligent Manufacturing for Tungsten, Molybdenum, and Rare Earth Industries

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INTRODUCTION TO CTIA GROUP

CTIA GROUP LTD, a wholly-owned subsidiary with independent legal personality established by CHINATUNGSTEN ONLINE, is dedicated to promoting the intelligent, integrated, and flexible design and manufacturing of tungsten and molybdenum materials in the Industrial Internet era. CHINATUNGSTEN ONLINE, founded in 1997 with www.chinatungsten.com as its starting point—China's first top-tier tungsten products website—is the country's pioneering e-commerce company focusing on the tungsten, molybdenum, and rare earth industries. Leveraging nearly three decades of deep experience in the tungsten and molybdenum fields, CTIA GROUP inherits its parent company's exceptional design and manufacturing capabilities, superior services, and global business reputation, becoming a comprehensive application solution provider in the fields of tungsten chemicals, tungsten metals, cemented carbides, high-density alloys, molybdenum, and molybdenum alloys.

Over the past 30 years, CHINATUNGSTEN ONLINE has established more than 200 multilingual tungsten and molybdenum professional websites covering more than 20 languages, with over one million pages of news, prices, and market analysis related to tungsten, molybdenum, and rare earths. Since 2013, its WeChat official account "CHINATUNGSTEN ONLINE" has published over 40,000 pieces of information, serving nearly 100,000 followers and providing free information daily to hundreds of thousands of industry professionals worldwide. With cumulative visits to its website cluster and official account reaching billions of times, it has become a recognized global and authoritative information hub for the tungsten, molybdenum, and rare earth industries, providing 24/7 multilingual news, product performance, market prices, and market trend services.

Building on the technology and experience of CHINATUNGSTEN ONLINE, CTIA GROUP focuses on meeting the personalized needs of customers. Utilizing AI technology, it collaboratively designs and produces tungsten and molybdenum products with specific chemical compositions and physical properties (such as particle size, density, hardness, strength, dimensions, and tolerances) with customers. It offers full-process integrated services ranging from mold opening, trial production, to finishing, packaging, and logistics. Over the past 30 years, CHINATUNGSTEN ONLINE has provided R&D, design, and production services for over 500,000 types of tungsten and molybdenum products to more than 130,000 customers worldwide, laying the foundation for customized, flexible, and intelligent manufacturing. Relying on this foundation, CTIA GROUP further deepens the intelligent manufacturing and integrated innovation of tungsten and molybdenum materials in the Industrial Internet era.

Dr. Hanns and his team at CTIA GROUP, based on their more than 30 years of industry experience, have also written and publicly released knowledge, technology, tungsten price and market trend analysis related to tungsten, molybdenum, and rare earths, freely sharing it with the tungsten industry. Dr. Han, with over 30 years of experience since the 1990s in the e-commerce and international trade of tungsten and molybdenum products, as well as the design and manufacturing of cemented carbides and high-density alloys, is a renowned expert in tungsten and molybdenum products both domestically and internationally. Adhering to the principle of providing professional and high-quality information to the industry, CTIA GROUP's team continuously writes technical research papers, articles, and industry reports based on production practice and market customer needs, winning widespread praise in the industry. These achievements provide solid support for CTIA GROUP's technological innovation, product promotion, and industry exchanges, propelling it to become a leader in global tungsten and molybdenum product manufacturing and information services.



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CTIA GROUP LTD

30 Years of Cemented Carbide Customization Experts

Core Advantages

30 years of experience: We are well versed in cemented carbide production and processing , with mature and stable technology and continuous improvement .

Precision customization: Supports special performance and complex design , and focuses on customer + AI collaborative design .

Quality cost: Optimized molds and processing, excellent cost performance; leading equipment, RMI, ISO 9001 certification.

Serving Customers

The products cover cutting, tooling, aviation, energy, electronics and other fields, and have served more than 100,000 customers.

Service Commitment

1+ billion visits, 1+ million web pages, 100,000+ customers, and 0 complaints in 30 years!

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Part 3: Performance Optimization of Cemented Carbide

Chapter 7: Mechanical Properties Control of Cemented Carbide

Cemented carbide (WC-Co) is widely used in aviation tools (cutting life > 15 hours), mining drill bits (drilling > 1200 m) and wear-resistant dies (extrusion > 10^6 times) due to its excellent high hardness (HV 1200-1800), good fracture toughness (K_{IC} 8-16 $\text{MPa} \cdot \text{m}^{1/2}$), high compressive strength (4000-6000 MPa) and excellent wear resistance (wear rate < $0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$). However, under extreme working conditions, such as high impact (frequency > 500 Hz), cyclic loading (> 10^5 times), high temperature (> 800°C) and abrasive wear (hardness > 800 HV), the comprehensive performance of cemented carbide still faces challenges. It is difficult for a single optimization strategy to simultaneously meet the synergistic requirements of hardness, toughness, fatigue resistance and wear resistance. A breakthrough in comprehensive performance can be achieved by controlling the microstructure (WC grain size 0.2-2 μm , Co content 6%-15%), in-depth analysis of failure mechanism (crack growth rate $\sim 10^{-6}$ mm/cycle) and applying advanced strengthening technology (additive VC 0.2%-0.5%, ion implantation dose 10^{16} - 10^{17} cm^{-2} , laser cladding thickness 50-150 μm).

This chapter starts from the following four aspects: balance between hardness and toughness, fatigue resistance and impact resistance, failure mechanism analysis and performance improvement strategy, systematically discussing the mechanical properties, advantages and disadvantages, regulation technology and conditions of cemented carbide. In addition, this chapter will also look forward to the development trend of cemented carbide under the future AI technology and industrial Internet of Things (IIoT) ecology, providing higher efficiency and reliability for industrial applications.

The advantages of cemented carbide are its high hardness and wear resistance, and its ability to withstand high loads and friction under extreme working conditions; however, its disadvantage is the contradiction between hardness and toughness. High hardness (HV > 1600) usually leads to a decrease in toughness ($K_{IC} < 10 \text{ MPa} \cdot \text{m}^{1/2}$), which is prone to brittle fracture. In addition, the fatigue resistance of cemented carbide still needs to be improved under high-frequency cyclic loading (the crack growth rate needs to be controlled at < 10^{-7} mm / cycle). Through the analysis in this chapter, readers will have a comprehensive understanding of the methods for regulating the mechanical properties of cemented carbide and its performance in practical applications.

7.0 Mechanical Properties of Cemented Carbide

Cemented carbide (WC-Co) is widely used in aviation, mining and mold manufacturing due to its excellent mechanical properties. The following is a detailed description of its main mechanical properties, including definition, measurement method, influencing factors and application background:

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7.0. 1. High hardness of cemented carbide

7.0. 1. 0 What is the hardness of cemented carbide ?

The hardness of cemented carbide (WC-Co) refers to the ability of its surface to resist indentation or scratches by external objects (such as indenters), reflecting the material's resistance to plastic deformation and wear. As a composite material, cemented carbide consists of a hard phase of tungsten carbide (WC, hardness of about HV 2000-2500) and a bonding phase of cobalt (Co, hardness of about HV 300). The hardness of cemented carbide is usually between HV 1200-1800, and can be further increased to HV 2000-2500 through surface modification (such as carburizing, laser cladding). The level of hardness directly determines the durability of cemented carbide in high-load, high-friction environments, such as its performance in cutting, drilling, and mold manufacturing.

The physical nature of hardness is closely related to the microstructure of the material, which is mainly due to the high hardness and grain boundary strengthening effect of the WC phase, while the Co phase absorbs part of the energy through plastic deformation and adjusts the overall performance.

7.0.1.1 Method for measuring hardness of cemented carbide

The hardness of cemented carbide can be measured by a variety of test methods, different methods are suitable for different scenarios and accuracy requirements:

Vickers hardness (HV)

Range : HV 1200-1800, up to HV 2000-2500 after surface modification.

Principle : Use a Vickers hardness tester, a diamond quadrangular pyramid indenter (diagonal angle 136°), apply a standard load (usually 30 kg), and calculate the hardness value by measuring the diagonal length of the indentation. The formula is:

$$HV = \frac{1.8544 \cdot F}{d^2}$$

Where F is the load (kg) and d is the diagonal length of the indentation (mm).

Advantages : wide measuring range, high accuracy, suitable for hardness testing of cemented carbide, and is the most commonly used method.

Application : Used to evaluate bulk hardness and the hardness of microscopic areas such as grains or coatings.

Rockwell hardness (HRA)

Range : HRA 80-94 (A scale).

Principle : Use a Rockwell hardness tester with a diamond cone indenter (cone angle 120°) and apply a load of 60 kg to measure the indentation depth.

Advantages : Fast testing, suitable for large-scale testing.

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Limitations : Slightly lower accuracy for superhard materials (such as cemented carbide), often used for preliminary evaluation.

Brinell hardness (HB)

Range : HB 1000-1600.

Principle : Use a carbide ball (10 mm diameter) indenter, apply a large load (such as 3000 kg), and calculate the hardness through the indentation area. The formula is:

$$HB = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})}$$

7.0.1.2 Factors affecting hardness

The hardness of cemented carbide is affected by a variety of microstructures and process parameters. The following is a detailed analysis of the main factors:

(1) WC grain size

效应: 晶粒尺寸越小, 硬度越高, 遵循 Hall-Petch 关系 ($\sigma_y = \sigma_0 + k \cdot d^{-1/2}$), 其中 σ_y 为屈服强度, d 为晶粒尺寸, k 为常数 (约 $0.3 \text{ MPa} \cdot \text{m}^{1/2}$)。硬度与屈服强度近似正比 ($HV \approx 3\sigma_y$)

data When the grain size decreases from $2 \mu\text{m}$ to $0.5 \mu\text{m}$, the hardness increases from HV 1200 to HV 1600, an increase of about 25%-30%. If the grain size is further reduced to $<0.2 \mu\text{m}$, the hardness can reach HV 1800, but the toughness may decrease due to grain boundary sliding.

mechanism Small grains increase the grain boundary density ($>10^{13} \text{ m}^{-2}$), hindering dislocation motion and thus increasing hardness.

(2) Co content

Effect : Co is a soft phase (hardness about HV 300), and increasing its content will reduce the hardness of cemented carbide.

Data : When the Co content is 6%-8%, the hardness is HV 1600-1800; when the Co content is 12%-15%, the hardness drops to HV 1200-1400.

Mechanism : When the Co content is high, the WC volume fraction decreases (WC proportion drops from 90% to 70%), and the deformation resistance of the hard phase decreases.

(3) Additives

Effect : Additives such as VC (vanadium carbide) or Cr_3C_2 can inhibit grain growth and increase hardness.

Data : Adding 0.2%-0.5% VC can increase the hardness by 5%-10%, up to HV 2000. If the addition amount is $>0.8\%$, brittle phases (such as VC_x) may be formed, which will reduce the performance.

Mechanism : VC inhibits grain growth and reduces grain boundary migration rate ($<10^{-10} \text{ m/s}$) through solid solution and precipitation strengthening (forming a thin VC_x layer with a thickness of $<20 \text{ nm}$).

(4) Surface modification

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Effect : Improve surface hardness through techniques such as carburizing, ion implantation or laser cladding .

Data : Carburizing forms a WC-rich layer (thickness 10-30 μm) with a hardness of up to HV 2000-2200; laser cladding forms a high-hardness layer (thickness 50-100 μm) with a hardness of up to HV 2500.

Mechanism : Surface modification introduces high hardness phase (such as WC or CrN) and residual compressive stress ($>400\text{ MPa}$) to enhance deformation resistance.

(5) Sintering process

Effect : Sintering temperature and atmosphere affect grain growth and microstructure.

Data : When the sintering temperature is 1400-1500°C and the vacuum degree is $<10^{-2}\text{ Pa}$, the grain size can be controlled to $<0.8\text{ }\mu\text{m}$ and the hardness reaches HV 1600. If the temperature is $>1550^\circ\text{C}$ and the grain size is $>2\text{ }\mu\text{m}$, the hardness decreases by 10%-15%.

Mechanism : High temperature causes grain growth and reduces the grain boundary strengthening effect.

7.0.1.3 Microscopic mechanism of hardness

The microscopic mechanism of cemented carbide hardness is mainly based on the following aspects:

(1) High hardness of WC phase

WC (tungsten carbide) is a superhard material with a hardness of up to HV 2000-2500, which is derived from its covalent bond structure (WC bond energy $\sim 800\text{ kJ/mol}$) and high modulus ($E \approx 700\text{ GPa}$). The WC phase accounts for 70%-90% of the volume fraction in cemented carbide and is the main source of hardness.

(2) Grain boundary strengthening (Hall-Petch effect)

晶粒尺寸减小增加晶界密度，晶界通过钉扎位错（Orowan 强化， $\tau \sim Gb/\lambda$ ， $\lambda < 1\text{ }\mu\text{m}$ ）阻碍位错运动，提高硬度和强度。晶界迁移速率（ $<10^{-10}\text{ m/s}$ ）受添加剂和烧结温度控制，迁移能障约为 80-120 kJ/mol。

(3) Regulatory effect of Co phase

The Co phase (low hardness, HV ≈ 300) absorbs part of the energy through plastic deformation (strain rate $\sim 10^{-3}\text{ s}^{-1}$) and reduces stress concentration, but high Co content will reduce the proportion of WC phase and reduce the overall hardness.

(4) Interface effect

The interface bonding strength ($>50\text{ MPa}$) between WC and Co has an important influence on the hardness. The wettability of Co on WC (contact angle $<15^\circ$) ensures low interface energy ($<1.5\text{ J/m}^2$), but if the Co distribution is uneven (deviation $>1\%$), Co pools (size $>5\text{ }\mu\text{m}$) may form, reducing the hardness.

(5) Thermodynamic stability

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The thermodynamic stability of fine-grained WC is evaluated by Gibbs free energy ($\Delta G < 0$). When the grain size is $< 0.5 \mu\text{m}$, the interface energy ($> 1.5 \text{ J/m}^2$) dominates the property changes and may induce microcracks (length $0.05\text{--}0.1 \mu\text{m}$), affecting the hardness.

7.0.1.4 Application significance of hardness

The high hardness of cemented carbide is its core advantage in industrial applications, especially in the following scenarios:

Aviation tools

Requirements : Cutting speed $> 800 \text{ m/min}$, high load and friction.

Performance : The cutting life of a WC-10Co tool with a hardness of HV 1600 can reach 15 hours, which is 25% higher than that of a material with a hardness of HV 1200.

Mechanism : High hardness reduces tool wear rate ($< 0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$) and extends tool life.

Mining drill bits

Requirements : Hard rock drilling (rock hardness $> 800 \text{ HV}$), high friction and impact resistance required.

Performance : WC-8Co drill bit with hardness HV 1700, drilling distance $> 1200 \text{ m}$, an increase of 40%.

Mechanism : High hardness reduces abrasive wear (groove width $< 10 \mu\text{m}$) and improves durability.

Wear-resistant mold

Requirements : High-frequency extrusion ($> 10^6$ times), resistance to wear and deformation.

Performance : WC-12Co die with hardness HV 1600, extrusion times $> 10^6$ times.

Mechanism : High hardness ensures the mold surface's ability to resist indentation and prolongs its life.

High temperature conditions

Demand : High temperature cutting ($> 800^\circ\text{C}$), such as aviation turbine blade processing.

Performance : Carbide with hardness HV 2000 (after carburizing) has a service life of 20 hours, an increase of 30%.

Mechanism : High hardness and oxide layer (WO_3 , thickness $\sim 2 \mu\text{m}$) jointly reduce high temperature wear.

7.0.1.5 Trade - off between hardness and toughness

- off between the hardness and toughness (K_{IC}) of cemented carbide:

High hardness ($\text{HV} > 1600$) is usually accompanied by low toughness ($K_{IC} < 10 \text{ MPa} \cdot \text{m}^{1/2}$), which can easily lead to brittle fracture due to fine grains ($< 0.2 \mu\text{m}$) or low Co content ($< 6\%$).

High toughness ($K_{IC} > 12 \text{ MPa} \cdot \text{m}^{1/2}$) requires increasing the Co content ($> 12\%$) or grain size ($1\text{--}2 \mu\text{m}$), but the hardness will decrease ($\text{HV} < 1400$), affecting wear resistance.

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Optimization strategies include:

The selected grain size is $0.5\text{--}1\ \mu\text{m}$, Co content is 8%-12%, hardness is HV 1500-1600, K_{IC} 12-14 $\text{MPa}\cdot\text{m}^{1/2}$.

Adding VC/ TaC (0.2%-0.5%) can increase the hardness by 3%-5% while maintaining toughness. Adopts gradient structure (surface Co 6%, internal 12%), surface hardness HV 1600, internal K_{IC} 14 $\text{MPa}\cdot\text{m}^{1/2}$.

7.0.1.6 Summary

The hardness of cemented carbide is the core indicator of its ability to resist deformation and wear, with a typical range of HV 1200-1800 and a maximum of HV 2500. The hardness is mainly contributed by the high hardness and grain boundary strengthening of the WC phase, and is affected by factors such as grain size, Co content, additives and surface modification. By optimizing the microstructure and process parameters, cemented carbide can demonstrate excellent durability and reliability in fields such as aviation, mining and mold manufacturing. In the future, the use of AI and Industrial Internet of Things (IIoT) technology can further improve hardness consistency and performance optimization efficiency.

7.0. 2. Fracture toughness of cemented carbide

The fracture toughness of cemented carbide (WC-Co) is its ability to resist crack propagation and fracture, and is a key indicator for evaluating the reliability of materials under high stress or impact conditions. The following is a detailed explanation of the definition, measurement method, influencing factors, microscopic mechanism and application significance.

7.0.2.1. Definition of fracture toughness of cemented carbide

Fracture toughness (K_{IC}) is the ability of cemented carbide to resist crack propagation when cracks or defects exist, and the unit is $\text{MPa}\cdot\text{m}^{1/2}$. The fracture toughness range of cemented carbide is usually 8-16 $\text{MPa}\cdot\text{m}^{1/2}$, reflecting its resistance to brittle fracture under high load or impact environment. Fracture toughness mainly depends on the plastic deformation ability of the bonding phase Co and the grain boundary strengthening effect of the WC phase, reflecting the balance between the hardness and toughness of cemented carbide.

7.0.2.2. Measurement method of fracture toughness of cemented carbide

Fracture toughness is usually measured by standardized test methods. The following are common methods:

Single Edge Notched Beam (SENB)

Principle: Prefabricate a V-shaped or straight-edge notch on the specimen, use three-point bending loading, and measure the maximum stress before crack expansion. The formula is:

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原理：在试样上预制 V 型或直边缺口，采用三点弯曲加载，测量裂纹扩展前的最大应力。公式为：

$$K_{Ic} = \frac{P \cdot S}{B \cdot W^{3/2}} \cdot f\left(\frac{a}{W}\right)$$

其中 P 为载荷， S 为支座间距， B 和 W 分别为试样厚度和宽度， a 为裂纹长度， $f\left(\frac{a}{W}\right)$ 为几何修正因子。

Conditions: The specimen size is usually $55 \times 10 \times 10$ mm, and the notch depth is about 2 mm.

Advantages: Suitable for accurate measurement of cemented carbide, widely used in industrial standards.

Indentation method

of K_{Ic} from the crack length of the Vickers hardness indentation, based on an empirical formula for crack growth.

Advantages: No need for complicated sample preparation, suitable for rapid testing.

Limitations: Low accuracy, suitable for preliminary evaluation.

Other methods, such as the double cantilever beam method (DCB) or the compact tension method (CT), are suitable for specific research scenarios.

The SENB method has become the mainstream method for fracture toughness testing of cemented carbide due to its high accuracy and standardization.

7.0.2.3. Factors affecting the fracture toughness of cemented carbide

The level of fracture toughness is affected by a variety of microstructural and process parameters, as follows:

Co content

Effect: Co, as a tough phase, absorbs crack energy through plastic deformation. The higher the content, the better the toughness.

Data: When the Co content is 6%, K_{Ic} is about $8-10 \text{ MPa} \cdot \text{m}^{1/2}$; when the Co content is 12%-15%, K_{Ic} can reach $14-16 \text{ MPa} \cdot \text{m}^{1/2}$.

Mechanism: Increasing Co content ($>10\%$) enhances plastic dissipation (strain rate $\sim 10^{-3} \text{ s}^{-1}$) but reduces hardness ($\text{HV} < 1400$).

Grain size

Effect: Grain size has a dual effect on toughness, and moderate size optimizes performance.

When the grains are coarse (such as $1-2 \mu\text{m}$), $K_{Ic} > 12 \text{ MPa} \cdot \text{m}^{1/2}$; when the grains are too fine (such as $< 0.2 \mu\text{m}$), $K_{Ic} < 8 \text{ MPa} \cdot \text{m}^{1/2}$ due to grain boundary sliding (rate $\sim 10^{-9} \text{ m/s}$).

Mechanism: Coarse grains reduce the grain boundary density ($< 10^{13} \text{ m}^{-2}$), thus reducing the resistance to crack propagation; excessively fine grains increase grain boundary defects, which can easily cause microcracks.

additive

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Effect: Additives can strengthen grain boundaries or optimize microstructure and improve toughness.

Data: Adding TaC (0.2 %-0.5%) can increase K_{Ic} by about 5%-10%; adding VC (>0.8%) may form a brittle phase and reduce toughness .

Mechanism: TaC enhances grain boundary bonding strength (>150 MPa) and reduces intergranular fracture .

Sintering process

Effect: Sintering temperature and time affect Co distribution and grain boundary stability.

Data: When the sintering temperature is 1400-1500°C and the sintering time is 1-3 hours , K_{Ic} is stable at 12-14 MPa·m^{1/2} ; if >1550°C, the Co segregation rate is >1%, and K_{Ic} decreases by 5%-10%.

Mechanism: High temperature leads to the formation of Co pool (size > 5 μm), which reduces toughness.

7.0.2.4. Microscopic mechanism of fracture toughness of cemented carbide

The microscopic mechanism of fracture toughness mainly includes the following aspects:

Plastic deformation of Co phase Co phase absorbs crack energy through plastic deformation (strain ~0.05%-0.1%) and delays crack propagation. When the

Co content is 10%, plastic dissipation is significant and K_{Ic} can reach 12 MPa·m^{1/2} .

Crack deflection at WC grain boundaries

WC grain boundaries (0.5-1 μm) increase the crack propagation path length and reduce the crack propagation rate (<10⁻² m/s) by crack deflection (angle 20°-40°). The deflection effect is more pronounced in coarse grains (>1 μm).

Interface bonding

The interface bonding strength (>50 MPa) between WC and Co is achieved by Co wetting (contact angle <15°), and the interface energy is <1.5 J/m² . If there are many interface defects (>0.5%), the toughness decreases.

Microcrack suppression

additives (such as TaC) inhibit microcrack initiation (length <0.05 mm) through solid solution strengthening (grain boundary spacing <0.2 μm), increasing K_{Ic} by 5%-10%.

7.0.2.5. Application significance of cemented carbide fracture toughness

Fracture toughness is crucial in the practical application of cemented carbide, especially in high impact and cyclic loading scenarios:

Aviation tools

Requirements: Cutting speed > 800 m/min, need to withstand high impact and cyclic loading.

Performance: WC-8Co tool with K_{Ic} 12 MPa·m^{1/2} , life >15 hours.

Mechanism: High toughness reduces crack growth (rate <10⁻⁶ mm/cycle) and extends service life.

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Mining drill bits

Requirements: Hard rock drilling (frequency > 500 Hz), high impact resistance required.

Performance: WC-10Co drill bit with $K_{IC} \geq 13 \text{ MPa} \cdot \text{m}^{1/2}$, drilling distance >1200 m.

Mechanism: High toughness absorbs impact energy (>18 J) and reduces the risk of fracture.

Wear-resistant mold

Requirements: High frequency extrusion (>10⁶ times), fatigue fracture resistance is required.

Properties: WC-12Co die with $K_{IC} \geq 14 \text{ MPa} \cdot \text{m}^{1/2}$, extrusion times >10⁶.

Mechanism: High toughness delays the growth of micro cracks (length < 0.1 mm).

Deep sea conditions

Requirements: Pressure > 80 MPa, stress corrosion resistance required.

Properties: Gradient structure carbide with $K_{IC} \geq 14 \text{ MPa} \cdot \text{m}^{1/2}$, life span > 4 years.

Mechanism: High toughness and surface protection reduce corrosion crack propagation.

7.0.2.6. Optimization and future development of cemented carbide fracture toughness

To improve fracture toughness, the following strategies can be used:

Microstructure optimization: Select grain size of 0.5-1 μm , Co content of 10%-12%, K_{IC} can reach 12-14 $\text{MPa} \cdot \text{m}^{1/2}$.

Additive control: Adding 0.2%-0.5% TaC can increase K_{IC} by 5%-10%.

Surface strengthening: Apply TiN coating (thickness 1-3 μm) to reduce surface crack initiation and increase K_{IC} by 5%-10%.

AI and IIoT : Use AI to predict Co distribution and grain boundary stability (error < 0.2%), and combine IIoT to monitor crack propagation in real time (accuracy $\pm 0.02 \text{ mm}$) and improve toughness consistency (deviation < 0.5 $\text{MPa} \cdot \text{m}^{1/2}$).

Fracture toughness is the focus of cemented carbide performance optimization, especially under extreme working conditions. By optimizing microstructure and process parameters, cemented carbide can meet the needs of high-demand applications such as aviation, mining and deep sea. In the future, the integration of AI and industrial Internet of Things technologies will further promote toughness improvement and application expansion.

7.0.3. Compressive strength of cemented carbide

The compressive strength of cemented carbide (WC-Co) is an important mechanical property indicator of its ability to withstand damage under compressive loads, reflecting the material's ability to resist compression deformation and brittle fracture. The following is a detailed explanation of the definition, measurement method, influencing factors, microscopic mechanism, application significance, optimization and future development, and more details and data are added to deepen the analysis.

7.0.3.1. Definition of compressive strength of cemented carbide

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Compressive strength is the maximum stress before the material reaches failure under unidirectional compression load of cemented carbide, measured in MPa, with a typical range of 4000-6000 MPa. Compressive strength is a key parameter for cemented carbide under high load conditions, mainly supported by the ultra-high modulus (about 700 GPa) and grain boundary strengthening effect of the hard phase tungsten carbide (WC), while being regulated by the plastic properties of the bonding phase cobalt (Co). The level of compressive strength directly determines the reliability and durability of cemented carbide in extreme pressure environments (such as deep sea or high-speed cutting). For example, the compressive strength of WC-10Co alloy is usually between 4500-5000 MPa, and the specific value varies depending on the microstructure and process parameters.

7.0.3.2. Method for measuring the compressive strength of cemented carbide

Compressive strength is determined by a standardized compression test, the following are the specific methods and relevant details:

Compression test

Principle: Use a universal material testing machine or a special compression testing machine to apply a unidirectional compression load to a cylindrical or cubic specimen until the specimen undergoes plastic deformation or brittle fracture, and record the maximum stress. The formula is:

$$\sigma_c = \frac{F}{A}$$

其中 σ_c 为抗压强度 (MPa), F 为破坏时的最大载荷 (N), A 为试样初始截面面积 (mm²)。

Test conditions:

Specimen geometry: cylindrical (10 mm diameter, 20 mm height) or cubic (10 × 10 × 10 mm), with a diameter to height ratio of typically 1:2 to avoid barrel effects.

Loading rate: 0.5-1 mm/min, load slowly to ensure uniform stress distribution.

Environmental conditions: room temperature (20-25°C), humidity <50%, avoid interference from environmental factors.

Advantages: Directly reflects the bearing limit of the material under compression, and the test results are highly correlated with the actual application scenarios.

Limitations: The sample must be free of initial defects (e.g. porosity <1%), otherwise the result will be low; the sample geometry and friction effects may introduce errors, requiring the application of lubricants or correction factors.

Supplementary technology: Combination of strain gauges to measure transverse and longitudinal strains and calculate Poisson's ratio ($\nu \approx 0.2-0.25$) further verifies the compressive performance.

The compression test method is a standard method for measuring the compressive strength of cemented carbide and is widely used in industry and scientific research.

7.0.3.3. Factors affecting the compressive strength of cemented carbide

The compressive strength is affected by multiple factors including microstructure, composition ratio

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and preparation process. The specific analysis is as follows:

WC grain size

Effect: Grain refinement enhances compressive resistance by increasing grain boundary density.

Data: When the grain size is refined from 2 μm to 0.2-0.5 μm , the compressive strength increases from 4000 MPa to >4500 MPa, or even up to 5000 MPa; if the grain size is >2 μm , the compressive strength drops to 3500-4000 MPa.

Mechanism: Fine grains (<0.5 μm) according to the Hall-Petch relationship

机理: 细小晶粒 (<0.5 μm) 依据 Hall-Petch 关系 ($\sigma_y = \sigma_0 + k \cdot d^{-1/2}$, $k \approx 0.3 \text{ MPa} \cdot \text{m}^{1/2}$)

Improve yield strength, grain boundary density > 10^{13} m^{-2} effectively hinders dislocation movement.

Limitation: Too fine grains (<0.2 μm) may cause microcracks to initiate due to increased grain boundary defects (>0.5%), and the compressive strength may decrease by 5%-10%.

Co content

Effect: Too high Co content will weaken the compressive strength.

Data: When the Co content is 8%-12%, the compressive strength is stable at 4500-5000 MPa; when the Co content is >15%, the compressive strength drops to <3500 MPa; when the Co content is <6%, the compressive strength can reach 5000-6000 MPa, but the toughness decreases ($K_{Ic} < 10 \text{ MPa} \cdot \text{m}^{1/2}$).

Mechanism: Co is a soft phase (hardness HV ≈ 300). A high content (>15%) reduces the WC volume fraction (<70%), softens the material, and reduces the compressive bearing capacity. A low Co content increases the WC phase ratio but is prone to brittle fracture.

Optimization range: Co content of 10% is considered to be the best value for the balance between compression resistance and toughness.

Microstructure

Effect: The homogeneous microstructure significantly improves the compressive properties.

Data: When the grain boundary density is > 10^{13} m^{-2} and the porosity is <1%, the compressive strength is >5000 MPa; if the grain boundary defect rate is >2% or the porosity is >2%, the compressive strength decreases by 10%-15%.

机理: 均匀分布的 WC 相和 Co 相减少应力集中, 晶界通过 Orowan 强化 ($\tau \sim Gb/\lambda$, $\lambda < 1 \mu\text{m}$) 钉扎位错, 增强抗压能力; 孔隙或缺陷 (如尺寸 >5 μm) 成为应力集中源, 降低强度。

Process influence: Cold isostatic pressing (CIP, pressure 200-300 MPa) can increase the density to >99%, significantly improving the compressive resistance.

7.0.3.4. Micromechanism of compressive strength of cemented carbide

The microscopic mechanism of compressive strength involves the following aspects:

High modulus of WC phase

The elastic modulus of WC phase ($E \approx 700 \text{ GPa}$) provides a high compressive strength basis and resists compression deformation. WC volume fraction of 70%-90% is the main source of compressive strength, and its covalent bond structure (WC bond energy $\sim 800 \text{ kJ/mol}$) ensures

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excellent compressive performance.

Grain boundary strengthening

High grain boundary density ($>10^{13} \text{ m}^{-2}$) hinders dislocation movement through the Orowan strengthening mechanism. When the grain size is $<0.5 \mu\text{m}$, the strengthening effect is significant, and the compressive strength can increase by 20%-30%. The grain boundary migration rate ($<10^{-10} \text{ m/s}$) is controlled by the sintering temperature (1400-1500°C).

Plastic regulation of the Co

phase The Co phase (hardness $\text{HV} \approx 300$) absorbs the compressive energy through plastic deformation (strain rate $\sim 10^{-3} \text{ s}^{-1}$) and prevents brittle failure. At 10% Co content, plastic dissipation optimizes the balance between compressive strength and toughness.

Interface stability

The interfacial bonding strength ($>50 \text{ MPa}$) between WC and Co is achieved by Co wetting (contact angle $<15^\circ$) and interfacial energy $<1.5 \text{ J/m}^2$. If there are many interfacial defects ($>0.5\%$), such as Co pools (size $>5 \mu\text{m}$), the compressive strength decreases by 10%-15%.

Thermal stress effect

The sintering cooling rate ($3\text{-}5^\circ\text{C/min}$) controls thermal stress ($<100 \text{ MPa}$). Too fast cooling ($>10^\circ\text{C/min}$) may introduce microcracks and reduce the compressive strength by 5%-10%.

7.0.3.5. Application significance of cemented carbide compressive strength

High compressive strength makes cemented carbide widely used in high load and extreme environments. The following is a detailed analysis of specific scenarios:

Aviation tools

Requirements: Withstands local pressure $>4000 \text{ MPa}$ during cutting, requiring high compressive resistance to maintain edge integrity.

Performance: WC-10Co tools with a compressive strength of 5000 MPa have a life of >15 hours at cutting speeds $>800 \text{ m/min}$, which is 25% higher than materials with a compressive strength of 4000 MPa .

Mechanism: High compressive strength reduces edge compression deformation (strain $<0.1\%$), ensuring cutting accuracy and durability.

Deep sea drill

Requirements: Working in deep sea environment with pressure $>80 \text{ MPa}$, need to resist high compressive loads and seawater corrosion.

Performance: WC-8Co drill bit with compressive strength of 5500 MPa , drilling distance $>1500 \text{ m}$, pressure resistance improved by 40%, and service life extended to 5 years.

Mechanism: High compressive resistance to withstand deep sea high pressure ($>80 \text{ MPa}$), combined

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with CrN coating (thickness 2-4 μm) to reduce corrosion effects.

Pressure resistant mold

Requirements: High-frequency extrusion ($>10^6$ times) must withstand local high pressure (>5000 MPa) to avoid deformation or breakage.

Performance: WC-12Co die with 6000 MPa compressive strength, extrusion times $>10^6$ times, 30% higher than die with 4500 MPa compressive strength.

Mechanism: High compressive strength reduces mold surface indentations (depth <0.5 μm) and extends service life.

High temperature conditions

Requirements: High temperature cutting ($>800^\circ\text{C}$) requires resistance to thermal stress, such as aviation turbine blade processing.

Performance: Gradient structure cemented carbide (6% Co on the surface, 12% inside) with compressive strength of 4500 MPa, life span >4000 hours at 850°C , 35% higher than ordinary materials.

Mechanism: High compressive resistance combined with an oxide layer (WO_3 , thickness ~ 2 μm) to resist high temperature compression and reduce thermal stress (<150 MPa).

7.0.3.6. Optimization and future development of cemented carbide compressive strength

To further improve compressive strength, the following strategies can be adopted:

Microstructure Optimization:

The grain size is 0.2-0.5 μm , and the compressive strength can reach 5000-6000 MPa through high-energy ball milling (speed 300-500 rpm, time 20-40 hours).

The Co content is controlled at 8%-12% to ensure a balance between compression resistance and toughness ($K_{1c} > 12 \text{ MPa} \cdot \text{m}^{1/2}$).

Additive Control:

Adding 0.2%-0.5% VC or Cr_3C_2 can increase the grain boundary strength by 5%-10% and the compressive strength by 3%-5%.

Avoid additions $> 0.8\%$ to prevent the formation of brittle phases (ratios $> 0.5\%$).

Surface strengthening:

Applying CrN coating (thickness 2-4 μm , hardness HV 3000-3500) can improve the surface compressive resistance and increase the strength by 5%-10%.

Laser cladding (power 1.5-2.5 kW, thickness 50-100 μm) forms a high-hardness layer, which improves the compressive resistance by 10%-15%.

Process Optimization:

Sintering temperature $1400-1500^\circ\text{C}$, vacuum degree $<10^{-2}$ Pa, density $>99\%$, porosity $<1\%$.

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Cold isostatic pressing (CIP, pressure 200-300 MPa) increases density and compressive strength by 5%-10%.

AI and IIoT :

AI was used to predict grain boundary density and Co distribution (error < 0.2%), and ball milling parameters were optimized based on historical data (accuracy ± 0.5 h).

Combined with IIoT , real-time monitoring of stress distribution (accuracy ± 10 MPa) and grain size (deviation < 0.005 μm) can be achieved to improve compressive strength consistency (deviation < 2%).

On June 1, 2025, the xAI team is developing a compressive optimization model based on deep learning (DNN), which is expected to increase the compressive strength prediction accuracy to ± 50 MPa, assisting in deep-sea drill bit design.

Compressive strength is the core performance of cemented carbide under high load conditions. By optimizing microstructure, process parameters and emerging technologies, it can meet the needs of high-demand applications such as aviation, deep sea and mold manufacturing. With the in-depth application of AI and Industrial Internet of Things (IIoT), the compressive performance and production efficiency of cemented carbide will be further improved, and it is expected to achieve significant breakthroughs in the next 2-3 years.

7.0.4. Wear resistance of cemented carbide

The wear resistance of cemented carbide (WC-Co) is its ability to resist surface material loss and wear, and is a key performance indicator for measuring the durability of materials in high friction or abrasive environments. The following is a detailed explanation of the definition, measurement method, influencing factors, microscopic mechanism, application significance, optimization and future development.

7.0.4.1. Definition of wear resistance of cemented carbide

Wear resistance is the ability of cemented carbide to resist surface wear under friction, abrasive or contact loads, usually quantified by wear rate (unit: $\text{mm}^3 / \text{N} \cdot \text{m}$) or wear volume. Cemented carbide is widely used in high wear scenarios due to its excellent wear resistance, which is mainly due to the high hardness (about HV 2000-2500) of the hard phase tungsten carbide (WC) and the toughness support provided by the bonding phase cobalt (Co). Wear resistance directly affects the service life of cemented carbide in cutting, drilling and mold manufacturing.

7.0.4.2. Measurement method of wear resistance of cemented carbide

Wear resistance is usually determined by standardized wear tests. The following are common methods and relevant details:

Sand flow abrasion test (ASTM G65)

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Principle: Use sand flow as abrasive, apply load to simulate abrasive wear, and measure the volume loss of the sample after wear. The wear rate calculation formula is:

$$W_r = \frac{V}{F \cdot L}$$

Where W_r is the wear rate ($\text{mm}^3 / \text{N} \cdot \text{m}$), V is the wear volume (mm^3), F is the load (N), and L is the sliding distance (m).

Test conditions:

Grit: SiO_2 (hardness > 800 HV).

Sliding speed: 1-2 m/s, duration 30-60 minutes.

Environment: Room temperature (20-25°C), humidity <50%.

Advantages: It simulates actual abrasive wear conditions, and the test results are highly relevant to industrial applications.

Limitations: The particle size and uniformity of the sand need to be controlled, and the test results are affected by the friction coefficient.

Pin-on-disc wear test (ASTM G99)

Principle: The specimen acts as a pin in contact with a rotating disk, load is applied, and the mass loss or depth after wear is measured.

Advantages: Suitable for evaluating adhesive wear and surface fatigue wear.

Limitations: High hardness requirements for the disc material and the need to correct the frictional heat effect.

Three-body wear test

Principle: Introduce a third abrasive to simulate wear under complex working conditions and measure the width and depth of wear scars.

Advantages: Closer to actual application scenarios, such as wear of mining drill bits.

The sand flow wear test (ASTM G65) has become the mainstream method for testing the wear resistance of cemented carbide due to its strong simulation and high degree of standardization.

7.0.4.3. Factors affecting the wear resistance of cemented carbide

Wear resistance is affected by multiple factors including microstructure, composition ratio, working conditions and environmental factors. The specific analysis is as follows:

hardness

效应: 硬度越高, 耐磨性越好, 遵循 Archard 磨损公式 ($V = k \cdot F \cdot L / H$, H 为硬度)。

Mechanism: High hardness reduces abrasive cutting depth and surface groove width.

Limitation: Too high a hardness may reduce toughness and increase the risk of brittle wear.

Grain size

Effect: Grain refinement generally enhances wear resistance, but excessive grain refinement may

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have negative effects.

Mechanism: Moderate grain size increases grain boundary density and hinders the invasion of abrasive particles; excessively fine grains may cause grain boundary defects and lead to microcracks.

Co content

Effect: Wear resistance is better when the Co content is moderate.

Mechanism: A proper amount of Co provides plastic support and reduces adhesive wear; when it is too high, Co softens and increases material loss; when it is too low, it lacks toughness and is prone to brittle wear.

Operating temperature

Effect: High temperatures reduce wear resistance, especially when adhesive wear dominates.

Mechanism: High temperature softens the Co phase, increasing adhesive wear and material transfer.

Surface roughness

Effect: Surface smoothness improves wear resistance.

Mechanism: Low roughness reduces the initial wear points and reduces abrasive embedding.

Environmental corrosion

Effect: Corrosive environment accelerates wear.

Mechanism: The acidic environment dissolves the Co phase, forming corrosion pits and increasing wear.

7.0.4.4. Micromechanism of Wear Resistance of Cemented Carbide

The microscopic mechanism of wear resistance involves the following aspects:

High Hardness of WC Phase

The hardness of the WC phase (HV 2000-2500) resists abrasive cutting, reduces surface material loss, and is the main source of wear resistance.

Grain boundary strengthening

Grain boundaries hinder the invasion of abrasive particles through the Orowan strengthening mechanism, and moderate grain size (0.5-1 μm) has the best effect.

Lubricating effect of Co phase

When the amount of Co phase is appropriate, it provides lubrication and plastic cushioning, reducing adhesive wear; when it is too high, it increases material transfer.

The surface oxide layer

forms a WO_3 oxide layer at high temperature to reduce wear, but uneven layer thickness may cause peeling.

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Wear type

Abrasive wear: Hard particles cut the surface, forming grooves.

Adhesive wear: Co softening at high temperatures leads to material transfer.

Fatigue wear: Microcrack propagation under cyclic loading intensifies wear.

7.0.4.5. Application significance of cemented carbide wear resistance

Excellent wear resistance makes cemented carbide perform well in high friction scenarios. Specific applications include:

Aviation tools

Requirements: Cutting speed > 800 m/min, need to resist high friction and abrasive wear.

Mechanism: High hardness reduces cutting edge wear.

Mining drill bits

Requirements: Hard rock drilling (rock hardness > 800 HV), need to resist abrasive wear.

Mechanism: Grain refinement reduces groove width and extends service life.

Wear-resistant mold

Requirements: High frequency extrusion ($>10^6$ times), need to resist surface wear.

Mechanism: Low surface roughness reduces the initial wear point.

High temperature conditions

Demand: High temperature cutting ($>800^{\circ}\text{C}$), such as aviation turbine blade processing.

Mechanism: Surface coating reduces high temperature adhesive wear.

7.0.4.6. Optimization and future development of cemented carbide wear resistance

To further improve wear resistance, the following strategies can be adopted:

Microstructure Optimization:

The grain size of 0.5-1 μm is selected and achieved through high-energy ball milling to optimize wear resistance.

The Co content is controlled at 8%-12% to balance plasticity and hardness.

Additive Control:

Adding a small amount of VC or Cr_3C_2 can enhance grain boundary strength and reduce wear.

Avoid excessive addition to prevent the formation of brittle phase.

Surface strengthening:

Apply CrN coating to increase surface hardness and reduce wear rate.

Laser cladding forms a high-hardness layer to further improve wear resistance.

Process Optimization:

Sintering temperature $1400-1500^{\circ}\text{C}$, vacuum degree $<10^{-2}\text{ Pa}$, ensure high density.

Surface polished to low roughness to reduce initial wear.

AI and IIoT :

Leverage AI to predict wear behavior and optimize microstructure design.

Combined with IIoT, real-time monitoring of friction coefficient and surface condition can improve wear resistance consistency.

Wear resistance is the core performance of cemented carbide under high friction conditions. By

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optimizing microstructure, surface treatment and emerging technologies, it can meet the high requirements of aviation, mining and high-temperature processing. With the in-depth application of AI and Industrial Internet of Things (IIoT), the wear resistance and production efficiency of cemented carbide are expected to be significantly improved in the next 2-3 years.

7.0.5. Fatigue resistance of cemented carbide

The fatigue resistance of cemented carbide (WC-Co) is its ability to resist fatigue failure and crack propagation under cyclic loading, and is an important mechanical property indicator to measure the durability of materials in long-term use. The following is a detailed explanation of the definition, measurement method, influencing factors, micro-mechanism, application significance, optimization and future development.

7.0.5.1. Definition of fatigue resistance of cemented carbide

Fatigue resistance refers to the ability of cemented carbide to resist the initiation and growth of fatigue cracks under repeated loading and unloading conditions, usually characterized by fatigue life (number of cycles) or crack growth rate (da/dN). The fatigue resistance of cemented carbide is mainly due to the hardness of the hard phase tungsten carbide (WC) and the toughness support provided by the bonding phase cobalt (Co), which is suitable for high-frequency cyclic loading scenarios, such as long-term use of cutting tools and drills.

7.0.5.2. Measurement method of fatigue resistance of cemented carbide

Fatigue resistance is usually determined by standardized fatigue tests. The following are common methods and relevant details:

Rotating bending fatigue test (ASTM E466)

Principle: The specimen is subjected to alternating bending loads in a rotating state, and the number of cycles before fatigue fracture is recorded. Fatigue life is expressed in cycles (N).

Test conditions:

Loading frequency: 10-50 Hz.

Stress ratio ($R = \sigma_{\min} / \sigma_{\max}$): 0.1-0.3.

Environment: Room temperature (20-25°C), humidity <50%.

Advantages: It simulates actual alternating stress conditions and is suitable for evaluating high cycle fatigue performance.

Limitations: The surface quality of the specimen needs to be controlled and the test results are affected by stress concentration.

Axial loading fatigue test (ASTM E606)

Principle: The specimen is subjected to axial alternating load and the fatigue life or crack growth rate is measured.

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Advantages: Suitable for evaluating low cycle fatigue and crack growth behavior.

Limitations: The test equipment has high requirements and the stress distribution needs to be corrected.

Crack growth test (ASTM E647)

Principle: Load is applied to a pre-cracked specimen and the relationship between the crack growth rate (da/dN) and the stress intensity factor (ΔK) is measured.

Advantages: Provides quantitative data on crack growth mechanisms.

Supplementary technology: Combined with optical microscopy (resolution $<1\ \mu m$) or scanning electron microscopy (SEM) to observe the crack morphology.

The rotary bending fatigue test has become the mainstream method for testing the fatigue resistance of cemented carbide due to its strong simulation and high degree of standardization.

7.0.5.3. Factors affecting fatigue resistance of cemented carbide

Fatigue resistance is affected by multiple factors such as microstructure, component ratio, loading conditions and environmental factors. The specific analysis is as follows:

Grain size

Effect: Grain refinement generally improves fatigue resistance.

Mechanism: Fine grains increase the density of grain boundaries and hinder crack propagation; excessively coarse grains may form stress concentration points.

Co content

Effect: Anti-fatigue performance is better when the Co content is moderate.

Mechanism: Appropriate amount of Co provides plastic buffer and reduces stress concentration; when it is too high, Co softens and reduces fatigue strength; when it is too low, it lacks toughness and is prone to cracks.

Stress ratio

Effect: Stress ratio affects fatigue life.

Mechanism: Low stress ratio ($R < 0.1$) increases fatigue life; high stress ratio ($R > 0.5$) accelerates crack growth.

Ambient humidity

Effect: High humidity reduces fatigue resistance.

Mechanism: When humidity increases, the Co phase may undergo slight corrosion, forming microcracks and accelerating fatigue failure.

Surface defects

Effect: Surface quality affects fatigue resistance.

Mechanism: Surface cracks or roughness ($Ra > 0.2\ \mu m$) become the source of fatigue cracks,

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reducing service life.

7.0.5.4. Microscopic mechanism of fatigue resistance of cemented carbide

The microscopic mechanism of fatigue resistance involves the following aspects:

High Hardness of WC Phase

The hardness of WC phase (HV 2000-2500) provides a basis for fatigue resistance and resists plastic deformation caused by cyclic stress.

Grain boundary strengthening

Grain boundaries hinder crack propagation through the Orowan strengthening mechanism, and moderate grain size (0.5-1 μm) has the best effect.

Plasticity regulation of Co phase

When the amount of Co phase is appropriate, it absorbs energy through plastic deformation and delays crack propagation; when it is too high, it increases fatigue damage.

Crack deflection

WC grain boundaries cause crack path deflection, increasing crack growth resistance.

Fatigue damage type

Surface initiation: Cyclic stress leads to surface microcracks (length < 0.1 mm).

Internal extension: The crack extends along the grain boundary or Co pool.

Fracture: Final fracture occurs after fatigue life is exhausted.

7.0.5.5. Application significance of fatigue resistance of cemented carbide

Excellent fatigue resistance makes cemented carbide perform well in cyclic loading scenarios.

Specific applications include:

Aviation tools

Requirements: High-frequency cutting (>500 Hz), resistance to cyclic fatigue.

Mechanism: High hardness reduces surface crack initiation and prolongs service life.

Mining drill bits

Requirements: Cyclic impact (frequency > 500 Hz), fatigue fracture resistance required.

Mechanism: Grain boundary strengthening delays crack propagation and improves durability.

Wear-resistant mold

Requirements: High frequency extrusion (>10⁶ times), fatigue resistance.

Mechanism: Low surface defects reduce fatigue crack sources.

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Mechanical Components

Requirements: Long-term cyclic loading, fatigue resistance is required.

Mechanism: Appropriate amount of Co improves toughness and delays fatigue damage.

7.0.5.6. Optimization and future development of fatigue resistance of cemented carbide

To further improve fatigue resistance, the following strategies can be adopted:

Microstructure Optimization:

The grain size of 0.5-1 μm is selected and achieved through high-energy ball milling to enhance grain boundary strengthening.

The Co content is controlled at 8%-12% to balance toughness and hardness.

Additive Control:

Adding a small amount of VC or TaC can enhance grain boundary strength and reduce crack propagation.

Avoid excessive addition to prevent the formation of brittle phase.

Surface strengthening:

Apply TiN or CrN coating to improve surface fatigue resistance.

Polish to low roughness ($R_a < 0.1 \mu\text{m}$) to reduce fatigue crack sources.

Process Optimization:

Sintering temperature 1400-1500°C, vacuum degree $< 10^{-2} \text{ Pa}$, ensure high density.

Control the cooling rate (3-5°C/min) to reduce thermal stress.

AI and IIoT :

Use AI to predict fatigue life and optimize microstructure design.

Combined with IIoT, real-time monitoring of stress distribution and crack propagation can improve fatigue resistance consistency.

Fatigue resistance is the core performance of cemented carbide under cyclic loading conditions. By optimizing microstructure, surface treatment and emerging technologies, it can meet the high requirements of aviation, mining and machinery manufacturing. With the in-depth application of AI and Industrial Internet of Things (IIoT), the fatigue resistance and production efficiency of cemented carbide are expected to be significantly improved in the next 2-3 years.

7.0.6. Impact resistance of cemented carbide

The impact resistance of cemented carbide (WC-Co) is its ability to resist fracture and deformation under high impact loads, and is an important mechanical performance indicator to measure the reliability of materials under dynamic loading environments. The following is a detailed explanation of the definition, measurement method, influencing factors, microscopic mechanism, application significance, optimization and future development.

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7.0.6.1. Definition of impact resistance of cemented carbide

Impact resistance refers to the ability of cemented carbide to resist crack initiation and fracture when subjected to instantaneous high-energy impact, usually characterized by impact energy (unit J) or impact toughness. The impact resistance of cemented carbide is mainly due to the toughness provided by the bonding phase cobalt (Co) and the hardness support of the hard phase tungsten carbide (WC), which is suitable for high-impact scenarios such as mining drills and high-speed cutting tools.

7.0.6.2. Measurement method of impact resistance of cemented carbide

Impact resistance is usually measured by standardized impact tests. The following are common methods and relevant details:

Charpy impact test (ASTM E23)

Principle: The specimen is impacted by a pendulum in a three-point bending state, and the energy required for fracture (impact work) is measured.

Test conditions:

Specimen dimensions: $55 \times 10 \times 10$ mm, with V-notch (depth 2 mm).

Impact speed: 5-5.5 m/s.

Environment: Room temperature (20-25°C).

Advantages: It simulates actual impact conditions, and the test results are highly correlated with the application scenarios.

Limitations: Notch shape and specimen size must be strictly controlled, and the results are affected by notch sensitivity.

Izod impact test (ASTM E23)

Principle: The sample is fixed in the form of a cantilever beam, subjected to the impact of a pendulum, and the fracture energy is measured.

Advantages: Suitable for small samples, easy to operate.

Limitations: Test results are affected by the way the specimen is clamped.

Drop weight impact test

Principle: A heavy hammer falls freely from a specified height to impact the sample and measure the material's impact resistance.

Advantages: Simulates high-energy impact and is suitable for evaluating dynamic performance.

Supplementary technology: Combine high-speed photography (frame rate > 1000 fps) to observe the fracture process, or use scanning electron microscopy (SEM) to analyze the fracture morphology. The Charpy impact test has become the mainstream method for testing the impact resistance of cemented carbide due to its high degree of standardization and strong simulation.

7.0.6.3. Factors affecting the impact resistance of cemented carbide

Impact resistance is affected by multiple factors such as microstructure, component ratio, test

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conditions and environmental factors. The specific analysis is as follows:

Co content

Effect: The higher the Co content, the better the impact resistance.

Mechanism: The Co phase absorbs impact energy through plastic deformation and reduces brittle fracture; when the Co content is too low, the brittleness of the material increases.

Grain size

Effect: Moderate grain size is beneficial to impact resistance.

Mechanism: When the grain size is moderate ($0.5-1\ \mu\text{m}$), grain boundary strengthening and toughness are balanced; too fine grains may cause grain boundary defects, and too coarse grains reduce the resistance to crack propagation.

additive

Effect: Additives can improve impact resistance.

Mechanism: Addition TaC or Cr_3C_2 enhances grain boundary strength and reduces intergranular fracture.

Test temperature

Effect: Low temperature reduces impact resistance.

Mechanism: Low temperature reduces the toughness of the Co phase and increases the tendency of brittle fracture.

Surface defects

Effect: Surface defects reduce impact resistance.

Mechanism: Surface cracks or roughness ($R_a > 0.2\ \mu\text{m}$) become stress concentration points, reducing the impact energy.

7.0.6.4. Microscopic mechanism of impact resistance of cemented carbide

The microscopic mechanism of impact resistance involves the following aspects:

Plastic absorption of Co phase

Co phase absorbs impact energy through plastic deformation, delaying crack propagation. Appropriate amount of Co improves impact toughness.

Crack deflection at WC grain boundaries

WC grain boundaries cause crack path deflection, increase the fracture path length and reduce the fracture velocity.

Grain boundary strengthening

Grain boundaries hinder crack propagation through the Orowan strengthening mechanism, and

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moderate grain size (0.5-1 μm) has the best effect.

Interfacial bonding

The interfacial bonding strength between WC and Co is achieved through Co wetting, and interfacial defects may trigger crack initiation.

Impact fracture type

Intergranular fracture : The crack extends along the WC grain boundary, which is more common when the Co content is low.

Transgranular fracture: The crack passes through the WC particles and is more common in high impact energies.

Mixed fracture: intergranular and transgranular fractures coexist, which is common in actual working conditions.

7.0.6.5. Application significance of cemented carbide impact resistance

Excellent impact resistance makes cemented carbide perform well in high impact scenarios. Specific applications include:

Mining drill bits

Requirements: High frequency impact (>500 Hz), resistance to impact fracture.

Mechanism: High Co content absorbs impact energy and reduces the risk of fracture.

Aviation tools

Requirements: High-speed cutting (>800 m/min), resistance to dynamic impact.

Mechanism: Grain boundary strengthening delays crack growth and extends service life.

Impact Die

Requirements: High frequency stamping ($>10^6$ times), resistance to impact failure.

Mechanism: Low surface defects reduce crack initiation.

Deep sea equipment

Requirements: Deep sea pressure shock (>80 MPa), need to resist dynamic loading.

Mechanism: Appropriate amount of Co and surface coating improve impact resistance.

7.0.6.6. Optimization and future development of cemented carbide impact resistance

To further improve impact resistance, the following strategies can be adopted:

Microstructure Optimization:

The grain size of 0.5-1 μm is selected and achieved through high-energy ball milling to optimize the balance between grain boundary strengthening and toughness.

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The Co content is controlled at 8%-12% to improve impact energy absorption.

Additive Control:

Adding a small amount of TaC or Cr₃C₂ can enhance the grain boundary strength and reduce intergranular fracture.

Avoid excessive addition to prevent the formation of brittle phase.

Surface strengthening:

Apply TiN or CrN coating to improve surface impact resistance.

Polish to low roughness ($R_a < 0.1 \mu\text{m}$) to reduce stress concentration points.

Process Optimization:

Sintering temperature 1400-1500°C, vacuum degree $< 10^{-2} \text{ Pa}$, ensure high density.

Control the cooling rate (3-5°C/min) to reduce thermal stress.

AI and IIoT :

Use AI to predict impact fracture behavior and optimize microstructure design.

Combined with IIoT, real-time monitoring of crack initiation and propagation can be used to improve impact resistance consistency.

Impact resistance is the core performance of cemented carbide under dynamic loading conditions. By optimizing microstructure, surface treatment and emerging technologies, it can meet the high requirements of mining, aviation and deep-sea equipment. With the in-depth application of AI and Industrial Internet of Things (IIoT), the impact resistance and production efficiency of cemented carbide are expected to be significantly improved in the next 2-3 years.

7.0.7. Comprehensive analysis and application of mechanical properties of cemented carbide

There are complex interactions and trade-offs between the mechanical properties of cemented carbide (WC-Co), which need to be comprehensively considered to meet the needs of different application scenarios. The following is a detailed analysis from the aspects of performance trade-offs, optimization strategies and future development.

7.0.7.1. Trade-offs between mechanical properties of cemented carbide

There is a certain trade-off between the mechanical properties of cemented carbide, which is reflected in the following aspects:

Hardness and toughness

Relationship: High hardness is usually accompanied by low toughness and vice versa.

Mechanism: High hardness (achieved by fine WC grains and low Co content) enhances deformation resistance, but reduces plasticity and fracture toughness (K_{IC}), which can easily lead to brittle fracture; high toughness (provided by higher Co content) absorbs energy through plastic

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deformation, but reduces hardness and weakens wear resistance .

Application impact: Aviation tools require high hardness to resist wear, while mining drills require high toughness to resist impact. The two need to be balanced according to specific working conditions.

Fatigue and shock resistance

Relationship: Fatigue resistance and impact resistance have different requirements on the microstructure.

Mechanism: Fatigue resistance depends on optimizing the microstructure (such as moderate grain size) to hinder crack propagation; impact resistance requires a higher Co content to improve energy absorption capacity and reduce instantaneous fracture.

Application impact: In high-frequency cyclic loading (such as aviation cutting tools), fatigue resistance is more important; in high-impact scenarios (such as mining drill bits), impact resistance takes precedence.

Wear resistance and environmental adaptability

Relationship: Wear resistance can be challenged in harsh environments such as high temperatures or corrosion.

Mechanism: High temperature ($>800^{\circ}\text{C}$) softens the Co phase and increases adhesive wear; the corrosive environment ($\text{pH} < 5$) causes the Co phase to dissolve, forming corrosion pits and accelerating wear.

Application impact: The processing of aviation turbine blades needs to consider high temperature wear resistance, and deep-sea drill bits need to pay attention to performance in corrosive environments.

7.0.7.2. Optimization strategies for mechanical properties of cemented carbide

In order to optimize the comprehensive performance of cemented carbide, the following strategies can be adopted:

Microstructure regulation

Grain size: Use WC grain size of $0.2\text{--}2\text{ }\mu\text{m}$. Fine grains ($<0.5\text{ }\mu\text{m}$) improve hardness and wear resistance, while larger grains ($1\text{--}2\text{ }\mu\text{m}$) enhance toughness and impact resistance.

Co content: controlled at 6%-15%. Low Co content (6%-8%) is suitable for high hardness requirements, and high Co content (12%-15%) is suitable for high toughness and impact resistance scenarios.

Additive Optimization

Adding a small amount of VC or TaC enhances grain boundary strength, improves wear resistance and fatigue resistance while maintaining toughness.

Avoid excessive addition to prevent the formation of brittle phase.

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Surface modification technology

Apply CrN or TiN coating to increase surface hardness and wear resistance and improve performance in high temperature and corrosive environments.

Laser cladding or ion implantation technology is used to form a high-hardness surface layer to enhance impact resistance and fatigue resistance.

7.0.7.3. Application scenarios of cemented carbide mechanical properties

Through comprehensive optimization, cemented carbide can meet the needs of the following demanding applications:

Aviation tools

Requirements: High hardness and wear resistance to resist cutting wear, high fatigue resistance to withstand cyclic loading.

Optimization strategy: grain size 0.2-0.5 μm , Co content 6%-8%, surface coating CrN.

Mining drill bits

Requirements: High toughness and impact resistance to withstand impact, high wear resistance to resist hard rock wear.

Optimization strategy: grain size 1-2 μm , Co content 12%-15%, adding TaC to strengthen grain boundaries.

Wear-resistant mold

Requirements: High hardness and wear resistance to resist extrusion wear, high fatigue resistance to extend service life.

Optimization strategy: grain size 0.5-1 μm , Co content 8%-12%, surface polished to low roughness.

7.0.7.4. Future development of mechanical properties of cemented carbide

In the future, the comprehensive performance and application reliability of cemented carbide can be further improved through the following technologies:

AI Technology: Use AI to predict performance trade-offs and optimize microstructure design (such as grain size and Co content).

Industrial Internet of Things (IIoT): Real-time monitoring of stress distribution and crack propagation during use to improve performance consistency.

Advanced manufacturing technology: Combining 3D printing and nanotechnology to develop gradient structure cemented carbide (such as high hardness on the surface and high toughness inside) to meet multifunctional needs.

Comprehensive analysis shows that the mechanical properties of cemented carbide need to be weighed and optimized to meet specific application requirements. By regulating microstructure, additives and surface modification technology, cemented carbide can be widely used in aviation,

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mining and mold manufacturing. In the future, the in-depth application of AI and Industrial Internet of Things (IIoT) will further promote its performance improvement and application expansion.

7.1 Hardness and toughness balance of cemented carbide

(1) Hardness of cemented carbide

The hardness of cemented carbide (WC-Co) refers to its ability to resist deformation and wear, usually expressed in Vickers hardness (HV), ranging from HV 1200-1800. The hardness is affected by the following factors:

WC grain size

(such as 0.2-0.5 μm), the higher the hardness, which can reach HV 1800 (Hall-Petch effect).

Co content

When the Co content is low (such as 6%-8%), the hardness is higher (HV 1600-1800); when the Co content is high (such as 12%-15%), the hardness decreases (HV 1200-1400).

as an additive

can inhibit grain growth and increase hardness by 5%-10%, up to HV 2000.

Surface modification

such as carburizing or laser cladding can increase the hardness to HV 2000-2500.

Hardness of cemented carbide

The hardness of cemented carbide (WC-Co) can be expressed in a variety of ways, depending on the test method and application scenario. Common expression methods include:

Vickers hardness (HV) range

of cemented carbide : HV 1200-1800, up to HV 2000-2500 (after surface modification).

Description: Use Vickers hardness tester to apply standard load (usually 30 kg) and calculate by indentation area.

Advantages: Suitable for a wide range of measurements of cemented carbide, reflecting the ability to resist deformation.

Rockwell Hardness (HR)

Range: HRA 80-94 (A scale).

Description: Use a diamond cone to apply a load of 150 kg and measure the indentation depth.

Advantages: Fast test, suitable for large-scale testing.

Brinell hardness (HB)

range: HB 1000-1600 (needs large load, such as 3000 kg).

Description: Use a steel ball or carbide ball to press in and calculate the indentation area.

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Limitations: Limited applicability to high hardness materials (such as carbide), load adjustment is required.

Microhardness (HV0.1-HV1)

Range: HV 1200-1800 (small load, such as 0.1-1 kg).

Description: Used for microscopic area measurement, especially suitable for analyzing grains or coatings.

Advantages: High accuracy, suitable for local property evaluation.

These representation methods reflect the ability of cemented carbide to resist compression, deformation and wear. Vickers hardness (HV) is the most commonly used due to its wide applicability. The actual value is affected by WC grain size, Co content and additives (such as VC can increase HV 5%-10%).

(2) Toughness of cemented carbide

The toughness of cemented carbide (WC-Co) is usually characterized by fracture toughness (K_{Ic}), which ranges from 8-16 $\text{MPa}\cdot\text{m}^{1/2}$. Its toughness characteristics are as follows:

Co content

, the better the toughness. When the Co content is 6%, K_{Ic} is about 8-10 $\text{MPa}\cdot\text{m}^{1/2}$; when the Co content is 12%-15%, K_{Ic} can reach 14-16 $\text{MPa}\cdot\text{m}^{1/2}$.

When the grain size

is coarse (such as 1-2 μm), the toughness is higher ($K_{Ic} > 12 \text{ MPa}\cdot\text{m}^{1/2}$); when the grain size is too fine (such as $< 0.2 \mu\text{m}$), the toughness may decrease due to grain boundary sliding ($K_{Ic} < 8 \text{ MPa}\cdot\text{m}^{1/2}$).

Adding TaC (0.2%-0.5%) as an additive

can strengthen grain boundaries and increase K_{Ic} by about 5%-10%.

The test method

uses the single edge notched beam method (SENB) test. For example, the K_{Ic} of WC-10Co (grain 0.5 μm , Co 10%) is about 12 $\text{MPa}\cdot\text{m}^{1/2}$, which is suitable for mining drill bits. Hardness and toughness need to be balanced, and high toughness is usually accompanied by a decrease in hardness (HV<1400).

(3) Types of toughness of cemented carbide

cemented carbide (WC-Co) is mainly characterized by the following indicators and methods, reflecting its ability to resist fracture and absorb energy:

Fracture toughness (K_{Ic}) of cemented carbide Fracture toughness (K_{Ic}) is the ability of cemented carbide to resist crack propagation when cracks exist, and its unit is $\text{MPa}\cdot\text{m}^{1/2}$

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² . K_{Ic} of cemented carbide is usually determined by the synergistic effect of hard phase tungsten carbide (WC) and binder phase cobalt (Co), reflecting the balance between hardness and toughness of the material.

K_{Ic}) of cemented carbide (WC-Co) is a key mechanical property index for its resistance to crack propagation and fracture, and plays a vital role in the reliability and service life of the material. The following is a detailed description of various aspects of importance and influencing factors.

Importance of fracture toughness of cemented carbide

Fracture toughness (K_{Ic}) is the core property of cemented carbide to maintain structural integrity under high stress, impact or defect conditions. Cemented carbide is widely used in cutting, drilling and mold making due to its high hardness (usually provided by WC, about HV 2000-2500), but this high hardness is often accompanied by high brittleness, making the material prone to irregular fracture when dynamically loaded or microcracks exist. K_{Ic} quantifies the material's ability to resist such brittle fracture and directly determines whether cemented carbide can withstand unexpected impact or defect-induced failure in actual use. For example, in a high-frequency impact or cyclic loading environment, a lower K_{Ic} may cause microcracks to quickly expand to macro fractures, while a higher K_{Ic} can significantly extend fatigue life and impact resistance. In addition, K_{Ic} also affects safety during processing, as sudden fracture of cemented carbide tools may cause production interruptions or equipment damage. Therefore, optimizing K_{Ic} is an important goal to improve the overall performance and reliability of cemented carbide in industrial applications, especially under extreme conditions (such as high temperature, high pressure or corrosive environment).

Factors affecting fracture toughness of cemented carbide

The fracture toughness of cemented carbide is affected by a variety of microstructures, composition ratios and preparation process parameters, as follows:

Co content

Function : Co, as a bonding phase, significantly affects K_{Ic} through its plastic deformation ability .

Mechanism : **When the Co content increases**, the proportion of tough phase in the material increases, which enhances the plastic dissipation capacity and inhibits crack propagation. When the Co content is low (such as 6% or less), the WC phase is dominant , and although the hardness is high, there is a lack of sufficient plastic buffer, resulting in a low K_{Ic} ; when the Co content is high (such as 12%-15%), the plasticity is enhanced and the K_{Ic} is significantly increased.

Range and balance : Typical Co content is between 6%-15%, with 10%-12% considered to be the optimal balance between toughness and hardness.

Limitations : Too high Co content may reduce hardness and wear resistance and needs to be adjusted according to specific needs.

Grain size

Effect : The effect of WC grain size on K_{Ic} is dual.

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机制：较细的晶粒（如 0.2-0.5 μm ）通过 Hall-Petch 效应 ($\sigma_y = \sigma_0 + k \cdot d^{-1/2}$) 增加晶界密度 ($>10^{13} \text{ m}^{-2}$)，提高强度，但可能因晶界缺陷（如空隙或微裂纹）降低 K_{IC} ；适中晶粒尺寸（0.5-1 μm ）提供最佳的晶界强化与韧性平衡；较大晶粒（ $>2 \mu\text{m}$ ）减少晶界密度，增强裂纹偏转能力， K_{IC} 随晶粒粗大而有所提升，但硬度可能下降。

Process influence : Grain size is controlled by sintering temperature (1400-1500°C) and time (1-3 hours). High temperature or long time sintering can easily lead to grain growth.

additive

Effect : Additives such as VC, TaC or Cr_3C_2 can significantly improve K_{IC} .

Mechanism : These additives strengthen grain boundaries by solid solution or precipitation, inhibit WC grain growth (grain boundary migration rate $<10^{-10} \text{ m/s}$), and enhance interface bonding strength ($>150 \text{ MPa}$). For example, VC (0.2%-0.5%) forms a VCx thin layer to reduce weak points at grain boundaries; TaC improves grain boundary toughness and reduces the tendency of intergranular fracture.

Limitations : Too high an addition (e.g. $>0.8\%$) may form a brittle phase (e.g. excessive VCx), which in turn reduces K_{IC} .

Microstructure uniformity

Effect : The uniformity of the microstructure directly affects K_{IC} .

Mechanism : Uniform distribution of WC and Co phases reduces stress concentration, and the structure with low porosity ($<1\%$) and few grain boundary defects ($<0.5\%$) enhances toughness. If Co is unevenly distributed (such as the formation of Co pools with a size of $>5 \mu\text{m}$), cracks are likely to propagate along weak areas, and K_{IC} decreases.

Process influence : Cold isostatic pressing (CIP, pressure 200-300 MPa) or vacuum sintering can improve microstructural homogeneity.

Sintering process

Effect : Sintering parameters affect the final performance of K_{IC} .

Mechanism : Sintering temperature (1400-1500°C) is too high or the sintering time is too long, resulting in coarse grains and Co segregation, reducing K_{IC} ; appropriate temperature and vacuum ($<10^{-2} \text{ Pa}$) ensure dense structure and optimize toughness. Cooling rate (3-5°C/min) controls thermal stress ($<100 \text{ MPa}$) and avoids microcrack formation.

Optimization : Multi-step sintering (such as low-temperature pre-sintering + high-temperature sintering) can improve microstructural consistency.

Surface state

Effect : Surface defects or residual stresses affect K_{IC} .

Mechanism : Surface cracks, roughness ($R_a > 0.2 \mu\text{m}$) or residual tensile stress ($>200 \text{ MPa}$) become crack initiation sources, reducing K_{IC} ; residual compressive stress ($>400 \text{ MPa}$) can increase K_{IC} through surface modification (such as shot peening).

Process influence : Polishing to $R_a < 0.1 \mu\text{m}$ or coating treatment (such as TiN) to improve surface

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condition.

Microscopic Mechanism

Plastic dissipation of Co phase : Co phase undergoes plastic deformation (strain rate $\sim 10^{-3} \text{ s}^{-1}$) under impact or stress , absorbing crack energy and delaying crack expansion.

Grain boundary deflection and bridging : WC grain boundaries cause crack deflection (angle 20° - 40°), increasing the path length; the Co phase forms a bridging effect at the crack tip, consuming energy.

Interface bonding strength : WC-Co interface (bonding strength $> 50 \text{ MPa}$, contact angle $< 15^{\circ}$) affects the crack propagation resistance, and interface defects (such as voids $> 0.5\%$) reduce K_{IC} .

Microcrack suppression : Additives strengthen grain boundaries, reduce microcrack initiation (length $< 0.05 \text{ mm}$), and improve overall toughness.

Fracture toughness is the core of cemented carbide performance optimization, which needs to be balanced by adjusting Co content, grain size, additives and preparation process to meet the needs under different working conditions.

(4) Impact Toughness of Cemented Carbide

The impact toughness of cemented carbide (WC-Co) is its ability to resist fracture and deformation under high-energy impact loads, and is an important mechanical property indicator for measuring the reliability of materials under dynamic loading environments. The following is a detailed explanation of its definition, importance, measurement method, influencing factors, and microscopic mechanism.

Definition of impact toughness of cemented carbide

Impact toughness refers to the ability of cemented carbide to absorb energy and resist fracture under instantaneous high-energy impact, usually characterized by impact energy (unit J) or fracture energy in impact test. The impact toughness of cemented carbide is mainly determined by the plastic deformation ability provided by the bonding phase cobalt (Co) and the hardness of the hard phase tungsten carbide (WC), reflecting the material's fracture resistance under high impact environment.

The Importance of Impact Toughness of Cemented Carbide

Impact toughness is crucial to the performance of cemented carbide under dynamic conditions. Cemented carbide is widely used in mining, cutting and mold manufacturing due to its high hardness (provided by WC, about HV 2000-2500), but high hardness is often accompanied by a certain brittleness, which makes it prone to brittle fracture under high impact loads (such as high-frequency impact or sudden load). Impact toughness directly determines whether cemented carbide can withstand such instantaneous loading without failure. For example, in mining drill bits or stamping dies, low impact toughness may cause the material to break quickly under high impact , causing equipment damage or production interruption; while high impact toughness can effectively extend the service life and improve safety. In addition, impact toughness also affects the reliability of cemented carbide in extreme environments (such as low or high temperatures), and is an important

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indicator for optimizing the comprehensive performance of materials.

Measuring method of impact toughness of cemented carbide

Impact toughness is usually determined by standardized tests. The following are common methods and relevant details:

Charpy impact test (ASTM E23)

Principle : The specimen is impacted by a pendulum in a three-point bending state, and the energy required for fracture (impact work) is measured.

Test conditions :

Specimen dimensions: $55 \times 10 \times 10$ mm, with V-notch (depth 2 mm).

Impact speed: 5-5.5 m/s.

Environment: Room temperature (20-25°C).

Advantages : It simulates actual impact conditions and the results are highly relevant to the application scenarios.

Limitations : Notch shape and specimen size need to be strictly controlled, and test results are affected by notch sensitivity.

Izod impact test (ASTM E23)

Principle : The sample is fixed in the form of a cantilever beam, subjected to the impact of a pendulum, and the fracture energy is measured.

Advantages : Suitable for small samples, easy to operate.

Limitations : Results are affected by the clamping method.

Drop weight impact test

Principle : A heavy hammer freely falls from a specified height to impact the sample and measure the impact resistance.

Advantages : Simulates high- energy impact and is suitable for evaluating dynamic performance.

Supplementary technology : Combine high-speed photography (frame rate > 1000 fps) to observe the fracture process, or use scanning electron microscopy (SEM) to analyze the fracture morphology. The Charpy impact test has become the mainstream method for testing the impact toughness of cemented carbide due to its high degree of standardization and strong simulation.

Factors affecting impact toughness of cemented carbide

The impact toughness of cemented carbide is affected by microstructure, composition ratio, test conditions and environmental factors, as follows:

Co content

Function : Co content is the main factor affecting impact toughness. The higher the Co content, the better the impact toughness.

Mechanism : Co phase absorbs impact energy through plastic deformation (strain rate $\sim 10^{-3} \text{ s}^{-1}$) and reduces the tendency of brittle fracture. When the Co content is low (such as 6% or less), the

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material is mainly WC phase, with high hardness but insufficient plasticity and poor impact toughness; when the Co content is high (such as 12%-15%), the plasticity is enhanced and the impact toughness is significantly improved.

Range and balance : The Co content is between 6%-15%, and 10%-12% is usually the optimal balance between toughness and hardness.

Limitations : Too high Co content may reduce hardness and wear resistance and needs to be adjusted according to application requirements.

Grain size

Effect : The effect of WC grain size on impact resistance is dual.

Mechanism : Moderate grain size (0.5-1 μm) provides the best balance between grain boundary strengthening and toughness. Grain boundary density ($>10^{13} \text{ m}^{-2}$) hinders crack propagation through the Orowan strengthening mechanism. Although finer grains ($<0.2 \mu\text{m}$) enhance hardness, grain boundary defects may increase, reducing impact toughness. Larger grains ($>2 \mu\text{m}$) increase crack deflection paths, impact toughness is improved, but hardness decreases.

Process influence : Grain size is controlled by sintering temperature (1400-1500°C) and time (1-3 hours). Too high temperature leads to coarse grains.

additive

Function : Additives such as TaC or Cr_3C_2 can improve impact toughness.

Mechanism : TaC enhances grain boundary strength ($>150 \text{ MPa}$) and reduces intergranular fracture; Cr_3C_2 inhibits grain growth (grain boundary migration rate $<10^{-10} \text{ m/s}$) and improves microstructural stability.

Limitations : Too high an addition (e.g. $>0.8\%$) may form a brittle phase and reduce impact toughness.

Test temperature

Effect : Temperature has a significant effect on impact toughness.

Mechanism : Low temperature ($<-40^\circ\text{C}$) reduces the toughness of the Co phase and increases the tendency of brittle fracture; high temperature ($>800^\circ\text{C}$) may cause the Co phase to soften and reduce the energy absorption capacity.

Environmental impact : The appropriate material formula needs to be selected according to the actual working conditions (such as deep-sea low-temperature or high-temperature cutting).

Microstructure uniformity

Function : Microstructure uniformity is crucial to impact resistance.

Mechanism : Uniformly distributed WC and Co phases reduce stress concentration, and structures with low porosity ($<1\%$) and few grain boundary defects ($<0.5\%$) enhance impact toughness. If Co is unevenly distributed (such as forming a Co pool with a size of $>5 \mu\text{m}$), cracks are likely to propagate along weak areas, reducing impact toughness.

Process influence : Cold isostatic pressing (CIP, pressure 200-300 MPa) or vacuum sintering can improve uniformity.

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Surface state

Effect : Surface defects or residual stress affect impact toughness.

Mechanism : Surface cracks, roughness ($R_a > 0.2 \mu\text{m}$) or residual tensile stress ($> 200 \text{ MPa}$) become stress concentration points, reducing impact toughness; residual compressive stress ($> 400 \text{ MPa}$) can improve impact resistance through surface modification (such as shot peening).

Process influence : Polishing to $R_a < 0.1 \mu\text{m}$ or coating treatment (such as TiN) to improve surface condition.

(5) Microscopic mechanism of impact toughness of cemented carbide

Plastic absorption of Co phase

The Co phase absorbs impact energy through plastic deformation and delays crack propagation. An appropriate amount of Co improves impact toughness.

Crack deflection at WC grain boundaries

WC grain boundaries cause crack path deflection (angle 20° - 40°), increase fracture path length, and reduce fracture velocity.

Grain boundary strengthening

晶界强化: 晶界通过 Orowan 强化机制 ($\tau \sim Gb/\lambda$, $\lambda < 1 \mu\text{m}$) 阻碍裂纹扩展, 适中晶粒尺寸 (0.5 - $1 \mu\text{m}$) 效果最佳。

Interface bonding

The interfacial bonding strength ($> 50 \text{ MPa}$) between WC and Co is achieved by Co wetting (contact angle $< 15^\circ$), and interfacial defects (e.g., voids $> 0.5\%$) may induce crack initiation.

Impact fracture type

Intergranular fracture : The crack extends along the WC grain boundary, which is more common when the Co content is low.

Transgranular fracture : The crack passes through the WC particles and is more common in high impact energies.

Mixed fracture : intergranular and transgranular fractures coexist, which is common in actual working conditions.

Impact toughness is the key performance of cemented carbide under dynamic loading environment. It can be optimized by adjusting the microstructure and process parameters to meet the requirements of different working conditions.

(6) Relationship between hardness and toughness of cemented carbide

There is a certain trade-off between the hardness and toughness (usually expressed as Vickers hardness HV and fracture toughness K_{Ic}) of cemented carbide (WC-Co). The basic relationship is as follows:

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Hardness (HV 1200-1800) and toughness (K_{IC} 8-16 $\text{MPa}\cdot\text{m}^{1/2}$) usually show an inverse trend. High hardness (such as HV 1600-1800) is often accompanied by lower toughness (K_{IC} 8-10 $\text{MPa}\cdot\text{m}^{1/2}$), while high toughness (K_{IC} 14-16 $\text{MPa}\cdot\text{m}^{1/2}$) usually leads to a decrease in hardness (HV 1200-1400). This is because hardness and toughness rely on different micromechanisms: hardness is mainly contributed by the high hardness of the WC phase, while toughness depends on the plastic deformation ability of the Co phase.

The hardness (HV 1200-1800) and fracture toughness (K_{IC} 8-16 $\text{MPa}\cdot\text{m}^{1/2}$) of cemented carbide are its core mechanical properties, which directly affect its reliability in high loads (>4000 MPa), impact environments (>500 Hz) and high temperatures (>800°C).

(7) The trade-off between hardness and toughness is a key challenge in cemented carbide design

High hardness (HV>1600) is usually accompanied by low toughness (K_{IC} <10 $\text{MPa}\cdot\text{m}^{1/2}$), which can easily lead to brittle fracture; while high toughness (K_{IC} > 12 $\text{MPa}\cdot\text{m}^{1/2}$) will reduce hardness (HV<1400) and weaken wear resistance. In order to balance the two, it is necessary to optimize the microstructure, including WC grain size (0.2-2 μm) and Co binder phase content (6%-15%), to meet the needs of demanding applications such as aviation tools (cutting life>15 hours) and mining drill bits (drilling>1200 m).

This section discusses the regulation mechanism of hardness-toughness balance from three aspects: grain size effect (based on Hall-Petch relationship), optimization of Co bonding phase content, and advanced technologies (such as nanocomposite technology and gradient structure design). It combines mechanical models (Hall-Petch: $\sigma_y \sim d^{-1/2}$, Orowan strengthening), thermodynamics (interface energy <1.5 J/m²) and process parameters (sintering temperature 1400-1500°C, vacuum degree <10⁻² Pa).

7.1.1 Grain size effect (Hall-Petch relationship)

7.1.1.1 Grain size effect

Grain size effect refers to the regular changes in the mechanical properties (such as hardness, strength and toughness) of materials such as cemented carbide with changes in grain size. According to the Hall-Petch relationship, a decrease in grain size (such as from 2 μm to 0.5 μm) will increase the grain boundary density (>10¹³ m⁻²), hinder dislocation movement, and thus increase hardness (by about 25%-30%, such as HV from 1200 to 1600) and strength.

Grain size effect principle and technology

Grain size is a key factor in regulating the hardness and toughness of cemented carbide, following the Hall-Petch relationship ($\sigma_y = \sigma_0 + k \cdot d^{-1/2}$, where σ_y is the yield strength, d is the grain size, and k is about 0.3 $\text{MPa}\cdot\text{m}^{1/2}$). Reducing the WC grain size (0.2-2 μm) can significantly

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increase the hardness (HV 1200-1800) and compressive strength (>4000 MPa). For example, after the grain size is refined from 2 μm to 0.5 μm , the hardness is increased from HV 1200 to HV 1600, and the cutting life of aviation tools is increased from 12 hours to 15 hours. However, grains that are too small (<0.2 μm) may induce microcracks due to grain boundary sliding (rate $\sim 10^{-9}$ m/s), resulting in a decrease in toughness ($K_{IC} < 8 \text{ MPa} \cdot \text{m}^{1/2}$). Therefore, optimizing the grain size requires a balance between grain boundary strengthening and interface stability.

The grain size is regulated by high-energy ball milling (speed 300-500 rpm, time 20-40 hours), adding grain inhibitors (such as VC 0.2%-0.5%, Cr_3C_2 0.1%-0.3%) and optimizing the sintering process (temperature 1400-1500°C, vacuum degree $< 10^{-2}$ Pa). In recent years, ultrafine-grained (<0.5 μm) and nanocrystalline (<100 nm) cemented carbides have become a research hotspot, and their hardness can reach HV 2000, but the problem of nanograin boundary stability needs to be solved (grain boundary migration rate $< 10^{-10}$ m/s).

7.1.1.2 Hall- Petch mechanism and mechanical analysis

What is Hall-Petch relationship ?

The Hall-Petch relationship is a very important fundamental principle in materials science , which describes the relationship between the grain size of a polycrystalline material and its yield strength . The relationship was independently discovered and formulated by EO Hall (1951) and NJ Petch (1953), and is therefore named after them. In simple terms , in the Hall-Petch relationship : **The finer the grains, the higher the strength (especially yield strength) of the material.**

This relationship can be expressed mathematically as follows:

$$\sigma_y = \sigma_0 + k \cdot d^{-1/2}$$

in:

σ_y : Yield strength of the material .

σ_0 : represents the yield strength of the material **single crystal** , or more generally, the resistance to dislocation motion inside the grain (lattice friction stress).

k: The **Hall-Petch slope** is a **constant** whose value depends on the material itself (such as crystal structure, dislocation characteristics) and the properties of the grain boundary (such as grain boundary energy, grain boundary sliding resistance). The larger the k value, the more significant the grain boundary strengthening effect.

d: **average grain diameter** of the material .

Core physical mechanism: grain boundaries hinder dislocation movement

Dislocation and plastic deformation

The plastic deformation of metal materials is mainly achieved through the slip of dislocations (linear defects in crystals) within the grains.

Grain boundaries as barriers

Grain boundaries are interfaces between adjacent grains. Due to the different crystal orientations of

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adjacent grains, it is difficult for dislocations to slide directly from one grain to the adjacent grain across the grain boundary.

Dislocation pile-up

Under the action of external stress, dislocation sources are activated and dislocations are generated. These dislocations move along the slip plane until they are blocked by the grain boundary, forming a "dislocation pileup" in front of the grain boundary.

Stress concentration and activation of dislocation sources in adjacent grains

The accumulated dislocation groups will produce a large local stress concentration at the grain boundary. When this concentrated stress reaches the stress required to activate the dislocation source in the adjacent grain, the plastic deformation can propagate to the next grain, and the material yields on a macro scale.

Grain refinement

The finer the grains (the smaller d is), the larger the grain boundary area per unit volume is, and the shorter the mean free path of dislocation slip is. Dislocations will encounter grain boundary obstacles in a shorter distance, and greater external stress is required to form a sufficiently strong dislocation pileup group in the grains (thus generating a sufficiently high stress concentration) to activate the dislocation source of the adjacent grains. Therefore, the yield strength σ_y of the material increases with the decrease of grain size d .

Significance of the Hall-Petch relationship

One of the most important reinforcement mechanisms

Grain refinement is one of the most effective and commonly used methods to improve the strength of metallic materials, and usually does not significantly reduce the toughness of the material (it may even improve the toughness, which is where it is superior to other strengthening mechanisms such as solid solution strengthening and precipitation strengthening).

Guidance material design

It provides a theoretical basis and quantitative tools for optimizing the mechanical properties of materials by controlling their microstructure (especially grain size). One of the core goals of metallurgical processes (such as controlled rolling, heat treatment, etc.) is to refine grains.

Understanding the size effect

Explains why nanocrystalline materials have extremely high strength.

The Hall-Petch relationship is very valid in the grain size range from micrometer to submicrometer (usually about $1\mu\text{m}$ to $0.1\mu\text{m}$). When the grain size decreases to the nanometer scale ($< 100\text{nm}$), other mechanisms (such as grain boundary sliding, dislocation absorption or emission at grain boundaries) may become dominant, and sometimes even the "reverse Hall-Petch effect" is observed, that is, the intensity decreases with further reduction of grain size.

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Material type applies primarily to **metals and alloys**. Similar relationships are observed in ceramics and some polymers, but the strengthening mechanisms may be different.

The Hall-Petch relationship shows that the smaller the grain size, the higher the grain boundary density ($>10^{13} \text{ m}^{-2}$), the dislocation movement is hindered, and the strength and hardness are significantly improved. Hardness (HV) is approximately proportional to yield strength ($HV \sim 3\sigma_y$). When the grain size decreases from $2 \mu\text{m}$ to $0.5 \mu\text{m}$, the hardness increases by about 25%-30% (from HV 1200 to 1600). However, if the grain size is too small ($<0.2 \mu\text{m}$), the grain boundary sliding intensifies, resulting in a decrease in toughness (K_{IC} drops from $12 \text{ MPa}\cdot\text{m}^{1/2}$ to $<8 \text{ MPa}\cdot\text{m}^{1/2}$). The mechanism is based on grain boundary strengthening and fracture mechanics: grain boundaries enhance performance by pinning dislocations (Orowan strengthening, $\tau \sim Gb/\lambda$, $\lambda < 1 \mu\text{m}$), but high grain boundary density increases interfacial energy ($>1.5 \text{ J/m}^2$) and easily induces microcracks (length $0.05\text{-}0.1 \mu\text{m}$).

Grain boundary dynamics analysis shows that the grain boundary migration rate (10^{-10} m/s) is controlled by sintering temperature ($1400\text{-}1500^\circ\text{C}$) and additives (VC 0.2%-0.5%), and the migration barrier is 80-120 kJ/mol. The thermodynamic stability of fine-grained WC is evaluated by Gibbs free energy ($\Delta G < 0$). When the grain size is $<0.5 \mu\text{m}$, the interface energy dominates the performance change. For example, WC-10Co (grain $0.5 \mu\text{m}$) has a hardness of HV 1600 and a K_{IC} of $12 \text{ MPa}\cdot\text{m}^{1/2}$, which is suitable for high-speed cutting ($>800 \text{ m/min}$).

7.1.1.3 Analysis of factors affecting grain size effect

The grain size effect is affected by the following factors:

Initial powder particle size

The particle size of WC powder is $0.5\text{-}1 \mu\text{m}$ to ensure uniform refinement; if it is $>2 \mu\text{m}$, the hardness is <1400 ; if it is $<0.2 \mu\text{m}$, the agglomeration rate is $>15\%$.

Ball milling time

Ball milling for 20-40 hours (rotation speed 300-500 rpm) can refine the grains to $0.5 \mu\text{m}$; if <15 hours, the grain size is $>1 \mu\text{m}$; if >50 hours, the grain breakage rate is $>3\%$.

Sintering temperature

$1400\text{-}1500^\circ\text{C}$ can control grain growth ($<0.8 \mu\text{m}$); if $>1550^\circ\text{C}$, the grain size is $>2 \mu\text{m}$ and the hardness decreases by 10%-15%.

additive

VC addition of 0.2%-0.5% can inhibit grain growth ($<0.5 \mu\text{m}$) and increase hardness by 5%-10%. If $>0.8\%$, a brittle phase is formed, resulting in $K_{IC} < 8 \text{ MPa}\cdot\text{m}^{1/2}$.

Co content

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Co content of 8%-12% can balance toughness; if $K_{1c} < 10 \text{ MPa} \cdot \text{m}^{1/2}$; if $> 15\%$, hardness < 1200 .

Sintering atmosphere: Vacuum degree $< 10^{-2} \text{ Pa}$ can avoid oxidation (O_2 content $< 0.5 \text{ ppm}$); using Ar atmosphere (purity $> 99.99\%$) can reduce grain boundary defects ($< 0.2\%$).

Cooling rate

Controlling the cooling rate at $3\text{-}5^\circ\text{C}/\text{min}$ can reduce thermal stress ($< 100 \text{ MPa}$); if $> 10^\circ\text{C}/\text{min}$, the microcrack rate is $> 0.5\%$.

Advantages, Disadvantages and Technical Requirements of Hall-Petch Relationship

Grain refinement significantly improves hardness and strength ($\text{HV } 1600$, $\sigma > 4500 \text{ MPa}$), making it suitable for high-load applications (such as aviation tools).

Too small grains ($< 0.2 \mu\text{m}$) will lead to decreased toughness ($K_{1c} < 8 \text{ MPa} \cdot \text{m}^{1/2}$), and the preparation cost of nanocrystalline WC is higher (about 20%-25% increase).

Technical conditions for Hall-Petch relationship

High-precision ball milling equipment (speed accuracy $\pm 5 \text{ rpm}$), online grain monitoring (deviation $< 0.02 \mu\text{m}$) and high-temperature and high-pressure sintering furnace (temperature deviation $< \pm 10^\circ\text{C}$, pressure deviation $< \pm 10^{-3} \text{ Pa}$) are required.

Optimization strategy

for Hall-Petch relationship To achieve high hardness ($\text{HV } 1600$) and moderate toughness ($K_{1c} > 12 \text{ MPa} \cdot \text{m}^{1/2}$), the following strategy is recommended:

Select WC powder with a particle size of $0.5\text{-}1 \mu\text{m}$ and perform high-energy ball milling for 20-40 hours (rotation speed 300-500 rpm).

The sintering temperature is controlled at $1400\text{-}1500^\circ\text{C}$, the vacuum degree is $< 10^{-2} \text{ Pa}$, and the grain size is $< 0.8 \mu\text{m}$.

Adding 0.2%-0.5% VC can inhibit grain growth and increase hardness by 5%-10%.

The Co content is set at 8%-12% to ensure $K_{1c} > 12 \text{ MPa} \cdot \text{m}^{1/2}$.

with online particle size monitoring (deviation $< 0.02 \mu\text{m}$).

The grain size was verified using TEM analysis (resolution $< 0.1 \text{ nm}$), and the grain boundary stress ($< 100 \text{ MPa}$) was evaluated using XRD (peak width deviation $< 0.2^\circ$).

Advanced technology: Try nanocomposite technology to form a dual-mode structure (grain size distribution: $0.2 \mu\text{m}$ and $1 \mu\text{m}$) by adding nano WC particles ($< 50 \text{ nm}$), the hardness is increased to $\text{HV } 1800$ and the K_{1c} reaches $13 \text{ MPa} \cdot \text{m}^{1/2}$.

Hall-Petch Relation Engineering Application Practice

Fine-grained cemented carbide performs well in a variety of scenarios:

Aviation tools

WC-10Co (grain size $0.5 \mu\text{m}$, hardness $\text{HV } 1600$) has a service life of 15 hours and a performance

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improvement of 25% in high-speed cutting (>800 m/min).

Mining drill bits

WC-8Co (grain size $0.8\ \mu\text{m}$, $K_{IC} \geq 13\ \text{MPa}\cdot\text{m}^{1/2}$) has a service life of 1,200 m in hard rock drilling, an increase of 40%.

Wear-resistant mold

WC-12Co (grain size $0.5\ \mu\text{m}$, hardness HV 1600), life span $>10^6$ times in extrusion.

Aviation turbine blades

WC-10Co (grain size $0.4\ \mu\text{m}$, VC 0.3%), hardness HV 1700, $K_{IC} \geq 12\ \text{MPa}\cdot\text{m}^{1/2}$, in high temperature cutting ($>800^\circ\text{C}$, speed >250 m/s), the service life reaches 20 hours, an increase of 30%.

New energy battery mold

WC-10Co (grain size $0.3\ \mu\text{m}$, hardness HV 1800), in high frequency extrusion (>500 Hz), life span $>10^6$ times, an increase of 50

7.1.2 Optimization of cemented carbide bonding phase content

Relationship between cemented carbide bonding phase type, content and toughness

The toughness of cemented carbide (represented by WC-Co) is closely related to the type and content of the bonding phase and the hard phase structure. The optimization of the bonding phase content (especially the cobalt content) is the core means to balance the hardness and toughness of the material, and its typical control range is 6%-15%. The following is a systematic analysis:

7.1.2.1 The core role of the bonding phase and technical regulation

The performance of cemented carbide is determined by the hard phase (carbides such as WC) and the metal bonding phase (mainly Co).

Co's core functions:

Plastic deformation carrier: When the crack propagates (strain rate is about $10^{-3}\ \text{s}^{-1}$), it absorbs energy through plastic deformation and directly contributes to toughness ($K_{IC} \geq 8-16\ \text{MPa}\cdot\text{m}^{1/2}$).

Interface bonding hub: Excellent wettability to WC (contact angle $<15^\circ$, interface energy $<1.5\ \text{J/m}^2$), forming a high-strength bonding interface ($>50\ \text{MPa}$).

Stress coordinator: relieves stress concentration between WC particles and prevents brittle fracture.

Technical principle of content optimization

Co content needs to be precisely controlled within the range of 6%-15%:

Low Co ($<6\%$): The hardness is significantly improved (HV >1600), but the toughness decreases sharply ($K_{IC} < 10\ \text{MPa}\cdot\text{m}^{1/2}$), and brittle fracture is prone to occur.

High Co ($>15\%$): Enhanced toughness ($K_{IC} > 14\ \text{MPa}\cdot\text{m}^{1/2}$), but insufficient hardness (HV <1200), and easy formation of Co pool (size $>5\ \mu\text{m}$), resulting in a 10%-15% decrease in strength.

Optimal balance point (8%-12%): Achieve synergy between hardness HV 1500 and toughness $K_{IC} \geq 12\ \text{MPa}\cdot\text{m}^{1/2}$ to meet high-demand scenarios such as aviation tools.

Implementation technology:

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Control the uniformity of Co distribution (deviation $<0.5\%$) through high-purity Co powder ($>99.9\%$) ratio $\rightarrow$ cold isostatic pressing (CIP, 200-300 MPa) $\rightarrow$ liquid phase sintering (1400-1500°C, 1-3 hours). The breakthrough technology in recent years is gradient structure design: by regulating the Co diffusion rate ($<10^{-9} \text{ cm}^2/\text{s}$), the surface Co content is reduced to 6% (hardness HV 1600) and the internal content is increased to 12% (toughness $K_{IC} 14 \text{ MPa}\cdot\text{m}^{1/2}$), achieving "hard surface and tough inside".

7.1.2.2 Quantitative effect of binder content on toughness

Co content is positively correlated with toughness, but the performance inflection point needs to be avoided:

Toughness improvement mechanism: Increase in Co content (6% $\rightarrow$ 12%) $\rightarrow$ thickening of metal layer $\rightarrow$ expansion of plastic

deformation space $\rightarrow$ crack propagation needs to pass through a thicker plastic zone, increasing K_{IC} from $10 \text{ MPa}\cdot\text{m}^{1/2}$ to $14 \text{ MPa}\cdot\text{m}^{1/2}$ ($K_{IC} \propto \text{Co}^{1/2}$).

Critical failure risk:

When the Co content is $>15\%$, the volume fraction of the hard phase is too low (WC accounts for $<85\%$), and the hardness drops below HV 1200;

When the sintering temperature is $>1550^\circ\text{C}$ or the Co distribution deviation is $>1\%$, a Co pool ($>5 \mu\text{m}$) is formed, which becomes the crack source and the toughness decreases by 10%-15%.

Mechanical model support:

Voigt model of composite materials:

$$E = V_{WC} \cdot E_{WC} + V_{Co} \cdot E_{Co}$$

Quantitative properties: Theoretical hardness of WC-10Co alloy HV 1500, $K_{IC} 12 \text{ MPa}\cdot\text{m}^{1/2}$.

7.1.2.3 Hierarchical relationship between bonding phase type and toughness

Cobalt (Co) - The Gold Standard:

The high dislocation energy gives excellent dislocation slip ability, significant work hardening effect, and the WC-Co system has the best toughness.

Nickel (Ni) based alloys - corrosion resistant alternatives:

Used in TiC - Ni - Mo, Cr_3C_2 - NiCr and other systems, but constrained by the carbide skeleton, the toughness is significantly lower than that of WC-Co with the same content (such as TiC - based alloy K_{IC} is usually $<10 \text{ MPa}\cdot\text{m}^{1/2}$).

Toughness shortcoming of special systems:

Although alloys based on metal carbides (such as TiC and Cr_3C_2 continuous skeletons) can improve toughness to a limited extent by increasing the Ni content, they are essentially limited by:

Intrinsic brittleness of carbides;

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The plasticity of the metal phase is constrained by the skeleton;
The interface bonding strength is weaker than that of Co-WC.

7.1.2.4 Strong Trade-off and Collaborative Optimization Strategy

Contradictory nature

Co content↑ → toughness↑↑ but hardness↓↓. Traditional homogeneous materials are difficult to meet extreme requirements.

Breakthrough Path

Grain refinement:

Control the WC particle size to 0.5-1 μm (if >2 μm, K_{IC} decreases by 5%-10%), and use fine grain strengthening to improve both strength and toughness.

Gradient structure design:

Low Co (6%) on the surface: achieves high hardness (HV 1600) and resists wear;

Internal high Co (12%): ensures high toughness (K_{IC} 14 MPa·m^{1/2}), and resistance to impact fracture;

Key technology: Add 0.2%-0.5% VC to inhibit Co diffusion, combined with layered sintering to control the composition gradient.

Process precision control:

Sintering: 1400-1500°C/vacuum degree <10⁻² Pa, time 1-3 hours (if >4 hours, Co segregation rate >1%);

Molding: CIP pressure 200-300 MPa, ensure density>99% (if <150 MPa, porosity>1%);

Quality inspection: EDS/EBSD (resolution <0.5 μm) was used to analyze the Co distribution, with a deviation of <0.5%.

7.1.2.5 Engineering practice verification

The optimized bonding phase design performs well in extreme working conditions:

Application Scenario	Material system	Performance parameters	Lifespan improvement
Aviation finishing tools	WC-10Co (0.5 μm)	HV 1500, K_{IC} 12 MPa·m ^{1/2}	>15 hours (+25%)
Deep sea drill	Gradient WC-Co (6% on the surface/12% inside)	Table HV 1600/Internal K_{IC} 14 MPa·m ^{1/2}	>1500 m (+50%)
High-speed rail brake pad mold	WC-10Co gradient	High temperature friction > 600°C	>4×10 ⁵ times (+60%)
Mining impact drill bit	WC-8Co	K_{IC} 13 MPa·m ^{1/2}	>1200 m (+40%)

7.1.2.6 Concluding Recognition

Co content is the core of toughness control: it is precisely optimized within the range of 6%-15%, and 8%-12% is the golden point of strength-toughness balance;

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The process determines the upper limit of performance:

Relying on high-purity raw materials (Co>99.9%), precision sintering ($\pm 2^{\circ}\text{C}$ temperature control) and non-destructive testing (X-ray/EDS deviation <0.2%);

Gradient structure is a revolutionary technology that breaks through the trade-off between strength and toughness, but the cost increases by 15%-20%;

Application-oriented design:

High toughness scenarios (mining, deep sea) $\rightarrow$ medium to high Co content (10%-15%) or gradient design;

High hardness scenario (finishing) $\rightarrow$ low Co (6%-8%) + fine grain WC ($0.5\ \mu\text{m}$) + VC additives;

Corrosion resistance/high temperature scenario $\rightarrow$ Nickel-based bonding phase alloys require compromise in toughness.

The toughness of cemented carbide is essentially the result of the synergistic effect of the content, type and microstructure of the bonding phase. Through scientific optimization of the Co content (6%-15%), gradient innovative design and precise process control, it can break through the traditional performance boundaries and meet the extreme needs from micron cutting to kilometer drilling.

7.2 Fatigue and impact resistance of cemented carbide

Fatigue resistance

The fatigue resistance of cemented carbide (WC-Co) refers to its ability to resist the initiation and expansion of fatigue cracks under cyclic loading, reflecting the durability of the material in long-term use. It mainly relies on optimizing the microstructure (such as grain size $0.5\text{-}1\ \mu\text{m}$) to reduce the crack growth rate, moderate Co content (8%-12%) provides plastic buffer, and grain boundary strengthening hinders crack growth. Measurement methods such as rotating bending fatigue test (ASTM E466) can evaluate its fatigue life.

Impact

resistance is the ability of cemented carbide to resist fracture under high-energy impact loads, reflecting its reliability under dynamic loading. It relies on high Co content (10%-15%) to absorb impact energy, moderate grain size ($0.5\text{-}1\ \mu\text{m}$) to balance toughness and strength, and additives (such as TaC) to strengthen grain boundaries. Charpy impact test (ASTM E23) is a common measurement method.

Fatigue resistance focuses on the uniformity of the microstructure and the crack propagation resistance, while impact resistance is more dependent on the plastic energy absorption of the Co phase. The two need to be balanced through microstructure optimization to meet the requirements of different working conditions.

The fatigue and impact resistance of cemented carbide under cyclic loading ($>10^5$ times) and high impact ($>500\ \text{Hz}$) directly determines its reliability in mining (drilling $>1200\ \text{m}$), aviation (tool

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life>15 hours) and die (extrusion>10⁶ times). Fatigue resistance is characterized by crack growth rate ($da/dN \sim 10^{-6}$ mm/cycle), and impact resistance is evaluated by impact energy (10-30 J). Optimization needs to start from microstructure (WC particle size 0.5-2 μm , Co content 6%-15%) and mechanical properties (stress intensity factor $\Delta K < 25 \text{ MPa} \cdot \text{m}^{1/2}$).

This section discusses the regulation mechanism of fatigue resistance and impact resistance from three aspects: crack propagation under cyclic loading (based on Paris's law), impact toughness test (Charpy and Izod) and advanced testing technology (such as in-situ SEM fatigue test). Combining fracture mechanics (Paris's law: $da/dN = C \cdot \Delta K^m$), experimental standards and application practices, this section discusses the regulation mechanism of fatigue resistance and impact resistance.

7.2.1 Crack growth of cemented carbide under cyclic loading (Paris law)

What is Paris's Law?

Paris' Law is a basic theoretical model that describes fatigue crack growth behavior. It is mainly used to predict the relationship between the crack growth rate and the stress intensity factor range of materials under cyclic loading. It is widely used in fatigue analysis of metals, composite materials and cemented carbides (such as WC-Co).

Paris's law expression

$$\frac{da}{dN} = C \cdot (\Delta K)^m$$

in:

$\frac{da}{dN}$: 裂纹扩展速率 (mm/循环), 表示每循环裂纹长度的增量。

ΔK : 应力强度因子范围 ($\text{MPa} \cdot \text{m}^{1/2}$), $\Delta K = K_{\max} - K_{\min}$, 其中 $K_{\max}$ 和 $K_{\min}$ 分别为最大和最小应力强度因子。

C 和 m : 材料常数, 依赖于材料类型、微观结构及环境条件。

For cemented carbide, m is usually in the range of 2-4 and C is smaller ($\sim 10^{-10}$ to 10^{-8}).

Paris's Law

Paris' law is applicable to the stable stage of fatigue crack growth (i.e., stage II), that is, the crack growth rate has a power law relationship with ΔK :

Stage I (threshold zone): $\Delta K < \Delta K_{th}$ (threshold), the crack does not extend.

Stage II (stable extension zone): The crack extends according to Paris' law.

Stage III (rapid fracture zone): $\Delta K \rightarrow K_c$ (fracture toughness), crack instability.

Application of Paris's Law in Cemented Carbide

The fatigue resistance of cemented carbide (WC-Co) can be analyzed by Paris law:

Micromechanism: Crack propagation is affected by WC grain boundaries and Co phase, and grain boundary deflection and Co plastic absorption energy reduce da/dN .

Factors affecting Paris's law

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Co content: Higher Co content (10%-15%) increases plasticity and reduces mmm.

Grain size: Moderate grains (0.5-1 μm) reduce d_a / d_N through grain boundary strengthening.

Environment: Corrosive environments (e.g. pH <5) may increase CCC.

Measurement: By crack growth test (ASTM E647), record d_a / d_N Relationship with ΔK , fitting CCC and mmm.

significance

Paris's law provides a theoretical basis for predicting the fatigue life of cemented carbide. It can be used to optimize the microstructure (such as grain size and Co content) and extend fatigue life. It is suitable for high-cycle loading scenarios such as aviation tools and mining drill bits.

Paris Law Principle and Technical Overview

Fatigue resistance is characterized by the crack growth rate (da/dN , unit: mm/cycle), which follows the Paris law: $da/dN = C \cdot \Delta K^m$

where ΔK is the stress intensity factor amplitude ($10^{-2.5} \text{ MPa}\cdot\text{m}^{1/2}$), C is $10^{-9} - 10^{-10}$, and m is 3-4.

Under cyclic loading (stress ratio R=0.1, frequency 5-15 Hz), the crack growth rate of cemented carbide needs to be controlled at $<10^{-6}$ mm/cycle to ensure a service life of $>10^5$ times. Optimization is achieved through grain refinement (WC 0.5-1 μm), Co content (8%-12%) and surface modification (such as ion implantation).

Fatigue testing is based on measuring crack length (accuracy ± 0.02 mm) under three-point bending (load 500-1000 N). In recent years, in-situ SEM fatigue testing (resolution <0.2 μm) has become a research hotspot, which can observe crack propagation paths (transgranular/intergranular ratio $<30\%$) and microscopic defects (pore size <2 μm) in real time.

Paris's Law - Mechanism and Mechanical Analysis

Paris's Law describes the behavior of steady crack growth (stage II):

ΔK calculation: $\Delta K = \Delta\sigma \cdot \sqrt{\pi a}$, where $\Delta\sigma$ is the stress amplitude and a is the crack length ($\sim 0.1 - 0.5$ mm). When $\Delta K < 20 \text{ MPa}\cdot\text{m}^{1/2}$, $d_a / d_N < 10^{-7}$ mm/cycle.

C and m parameters: C is $10^{-9} - 10^{-10}$, m is 3.2-3.8, reflecting the material's crack resistance. When the Co content is 10%, C decreases by 15%-20%.

Micromechanism: The Co phase dissipates crack energy through plastic deformation (strain $\sim 0.05\% - 0.1\%$), and the WC grain boundary (0.5 μm) hinders crack propagation (rate $<10^{-6}$ mm/cycle).

High temperature fatigue: At 800°C, the crack growth rate is $<10^{-5}$ mm/cycle, and the oxide layer (WO_3 , thickness ~ 2 μm) can reduce da/dN by about 5%-10%.

In-situ SEM analysis shows that the crack propagation path is mainly transgranular fracture (ratio $>50\%$), and when the grain boundary deflection angle is $20^\circ - 40^\circ$, d_a / d_N decreases by 10%-15%. For example, the crack growth rate of WC-10Co (ΔK is $15 \text{ MPa}\cdot\text{m}^{1/2}$) is about 10^{-7} mm/cycle, which meets the requirements of aviation tools.

Analysis of factors affecting crack propagation

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Crack propagation is affected by the following factors:

Grain size: 0.5-1 μm can reduce da/dN ($<10^{-7}$ mm/cycle); if $>2 \mu\text{m}$, $da/dN >10^{-6}$ mm/cycle.

Co content: 10% can optimize K_{Ic} ($>12 \text{ MPa}\cdot\text{m}^{1/2}$); if $<6\%$, da/dN increases by 20%-30%.

Stress ratio: When $R=0.1$, $da/dN <10^{-7}$ mm/cycle; if $R>0.5$, da/dN increases by 40%-50%.

Additives: VC addition of 0.2%-0.5% can improve the grain boundary strength ($>150 \text{ MPa}$); if $>0.8\%$, the brittle phase ratio is $>0.5\%$.

When $R_a<0.1 \mu\text{m}$, the crack initiation time is $>10^4$ times; if $>0.2 \mu\text{m}$, the service life decreases by 15%-20%.

Micro defects: When the porosity is $<1\%$, $da/dN <10^{-7}$ mm/cycle; if $>2\%$, da/dN increases by 30%-40%.

Ambient humidity: When relative humidity is $<50\%$, $da/dN <10^{-7}$ mm/cycle; if it is $>80\%$, corrosion fatigue causes da/dN to increase by 20%-25%.

Cemented carbide has excellent fatigue resistance (lifespan $>10^5$ times) and is suitable for high-frequency cyclic loading scenarios (such as mining drill bits). In a corrosive environment (humidity $>80\%$), fatigue life decreases by 15%-20%, and surface coatings (such as TiN, thickness 1-3 μm) are required to improve corrosion resistance. A high-precision fatigue tester (frequency deviation $<0.2 \text{ Hz}$), in-situ SEM (resolution $<0.2 \mu\text{m}$) and environmental control box (humidity accuracy $\pm 2\%$) are required.

Paris Law Optimization Strategy

To reduce the crack growth rate ($<10^{-7}$ mm/cycle), the following strategies are recommended:

The WC grain size is selected to be 0.5-1 μm and the Co content is 10%.

Adding 0.2%-0.5% VC can improve the grain boundary strength and reduce da/dN by about 15%-20%.

The surface is polished to $R_a<0.1 \mu\text{m}$ and the crack initiation time is $>10^4$ times.

Control stress ratio $R=0.1$ to ensure $\Delta K<20 \text{ MPa}\cdot\text{m}^{1/2}$.

Online crack monitoring (accuracy $\pm 0.02 \text{ mm}$) is used to ensure test consistency (da/dN deviation $<5\%$).

Sintered density $>99.5\%$, porosity $<1\%$, combined with fatigue testing machine (frequency deviation $<0.2 \text{ Hz}$).

Advanced technology: Application of TiN coating (thickness 1-3 μm , hardness HV 2500-3000) reduces the effects of corrosion fatigue and reduces da/dN by 10%-15%.

The performance of fatigue-resistant cemented carbide after optimization in engineering application of Paris Law is excellent:

Mining drill bit: WC-10Co (crack growth rate $\sim 10^{-7}$ mm/cycle), life $>10^5$ times in cyclic impact, drilling distance $>1200 \text{ m}$.

Aviation tools: WC-8Co ($K_{Ic} 13 \text{ MPa}\cdot\text{m}^{1/2}$), fatigue life $> 10^5$ times, cutting life >15 hours.

Wear-resistant mold: WC-12Co ($\Delta K<15 \text{ MPa}\cdot\text{m}^{1/2}$), extrusion times $>10^6$ times, increased by 25%.

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High-speed rail gears: WC-10Co (grain size $0.5\ \mu\text{m}$, TiN coating $2\ \mu\text{m}$), in high-frequency cycles ($>100\ \text{Hz}$), the crack growth rate is $\sim 10^{-8}\ \text{mm/cycle}$, and the life span is $>10^6$ times, an increase of 40%.

7.2.2 Impact toughness test of cemented carbide (Charpy and Izod)

Overview of the Principle and Technology of Cemented Carbide Impact Toughness Test

Impact toughness is the ability of hard alloy (WC-Co) to resist fracture under high-energy impact loads, and is a key indicator of its reliability in dynamic loading environments (such as high-frequency impact or transient loads). Impact toughness is characterized by the ability to absorb impact energy, usually expressed in impact energy (unit: J), which is mainly determined by the plastic deformation ability of the bonding phase cobalt (Co) and the hardness of the hard phase tungsten carbide (WC). The impact toughness test is designed to simulate actual working conditions (such as high-frequency impact of mining drill bits or dynamic loading of aviation tools) to evaluate the material's fracture resistance under high stress environments.

Test method overview:

The impact toughness of cemented carbide is mainly measured by two standardized test methods: Charpy and Izod. Both methods use a pendulum to impact the specimen and record the energy required for fracture (impact work), but there are significant differences in the specimen fixing method, loading mode and stress distribution.

Test equipment:

Pendulum energy: The standard equipment pendulum energy is 300 J.

Impact speed: 4-5 m/s.

Environmental control: Room temperature ($20-25^{\circ}\text{C}$) is the standard test condition. Low or high temperature tests require special temperature control devices.

High strain rate testing:

In recent years, high strain rate testing (strain rate $>10^3\ \text{s}^{-1}$) has become a research hotspot, which can more realistically simulate extreme working conditions such as explosive impact (speed $>50\ \text{m/s}$) or high-speed cutting. Under high strain rates, materials show more significant strain rate sensitivity, and impact toughness may decrease, requiring microstructure optimization to improve performance.

Charpy Impact Test Details

Concept and Principle:

Charpy impact test (ASTM E23) is a classic impact toughness test method. It uses a three-point bending loading method to measure the energy required for fracture by impacting the specimen with a pendulum. The specimen is a rectangular cross-section, usually with a V-notch to simulate the stress concentration points that may exist in actual working conditions. Impact energy reflects the ability of the material to absorb energy and resist crack propagation, and is an important indicator of the impact resistance of cemented carbide.

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Specimen and loading method:

Sample specifications:

Standard size: $55 \times 10 \times 10$ mm (length $\times$ width $\times$ height).

Notch type: V-notch, depth 2 mm, notch bottom radius 0.25 mm, notch angle 45° .

Notch effect: Stress concentration is formed at the notch tip, inducing crack initiation, which facilitates quantification of the material's sensitivity to defects.

Loading method:

The sample is placed horizontally on two fulcrums, and the pendulum falls freely from a certain height, hitting the center of the sample (the back of the notch) at a speed of 4-5 m/s. The sample is subjected to three-point bending stress, and the crack starts from the notch tip and expands until it breaks.

Stress distribution:

Under the three-point bending mode, tensile stress is generated at the notch of the specimen, the maximum tensile stress is concentrated at the bottom of the notch, and the stress concentration factor (K_t) is about 2-3. Impact energy includes crack initiation energy and crack extension energy, of which crack extension energy is dominant.

Testing process:

Specimen processing: The specimens are processed according to standard dimensions, and the notches are processed by wire cutting or special tools to ensure processing accuracy (± 0.02 mm).

Environmental control: The sample is placed at a specified temperature (such as room temperature $20-25^\circ\text{C}$ or low temperature -40°C) and regulated in a temperature control chamber.

Impact loading: release the pendulum, impact the specimen, record the height difference of the pendulum swing, and calculate the impact work:

$$\text{冲击功} = m \cdot g \cdot (h_{\text{初}} - h_{\text{终}})$$

in m is the mass of the pendulum, g is the acceleration due to gravity, h_{initial} and h_{final} are the initial and final heights respectively.

Features and applicability:

The Charpy test simulates the stress state of three-point bending in actual working conditions (such as the local stress when the drill bit impacts the rock).

It is suitable for evaluating the fracture resistance of cemented carbide under high impact environment, especially the toughness performance in the presence of defects (notches).

The test results are greatly affected by notch geometry, sample size and temperature, and the experimental conditions need to be strictly controlled.

Izod Impact Test Details

Concept and Principle:

Izod impact test (ASTM E23) is another standardized impact toughness test method, which uses cantilever beam loading to measure the energy required for fracture by impacting the free end of the specimen with a pendulum. The specimen is usually notched to evaluate the material's resistance to stress concentration and crack propagation. Compared with the Charpy test, the force mode of the Izod test is closer to some actual working conditions (such as cantilever structure being impacted).

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Specimen and loading method:

Sample specifications:

Standard size: $75 \times 10 \times 10$ mm (length $\times$ width $\times$ height).

Notch type: V-notch, depth 2 mm, notch bottom radius 0.25 mm, notch angle 45° .

Notch position: The notch is located near the fixed end of the specimen, about 22 mm away from the clamping end.

Loading method:

One end of the sample is fixed to the fixture, and the other end is suspended to form a cantilever beam structure. The pendulum hits the free end of the sample (the back of the notch) at a speed of 4-5 m/s. The sample is subjected to a composite stress of bending and shearing. The crack starts from the tip of the notch and expands until it breaks.

Stress distribution:

In the cantilever beam mode, the notch produces a superposition of tensile stress and shear stress. The maximum tensile stress is located at the bottom of the notch, and the shear stress is distributed along the thickness direction of the specimen. The stress concentration factor (K_t) is about 2.5-3.5, slightly higher than the Charpy test. The crack propagation path is affected by the shear stress and may propagate along the WC-Co interface or through the grain.

Testing process:

Specimen processing: The specimens are processed according to standard dimensions, and the notch processing accuracy is controlled within ± 0.02 mm.

Specimen clamping: The specimen is fixed in the fixture, ensuring that the clamping end does not slip or loosen.

Impact loading: The pendulum is released to impact the free end of the specimen, the height difference of the pendulum is recorded, and the impact energy is calculated (the formula is the same as the Charpy test).

Features and applicability:

The Izod test simulates the stress conditions of a cantilever beam structure (e.g. a machine component subjected to a lateral impact).

It is suitable for evaluating the impact resistance of cemented carbide under complex stress states, especially in scenarios where shear stress dominates.

Due to the complex specimen fixing method and stress distribution, the test results may be slightly lower than the Charpy test and are sensitive to the clamping conditions.

Comparison of Charpy and Izod tests

Stress mode: The

Charpy test is a three-point bending test, which is mainly affected by tensile stress; the Izod test is a cantilever beam test, where tensile stress and shear stress are superimposed, and the crack propagation path is more complicated.

Specimen fixation:

Charpy test specimens are supported at both ends, making fixation simple; Izod test specimens are clamped at one end, which places higher requirements on the fixture.

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Impact energy difference:

Due to the larger shear stress component of the Izod test, more crack growth energy is dissipated, and the impact energy is usually slightly lower than that of the Charpy test.

Application scenarios: The

Charpy test is more suitable for simulating symmetrical impacts (such as a drill bit being hit head-on); the Izod test is more suitable for simulating lateral impacts (such as mechanical cantilever parts).

Theoretical basis and mechanism analysis

Impact toughness testing is based on the principles of fracture mechanics. The impact energy is related to the fracture toughness (K_{Ic}), which can be estimated indirectly through the energy release rate (G_c):

$$K_{Ic} \approx \sqrt{E \cdot G_c}$$

where E is the elastic modulus (about 550-650 GPa for WC-Co) and G_c is the fracture energy (contributed by the plasticity of the Co phase and the crack growth resistance).

Charpy test mechanism:

The specimen is subjected to three-point bending impact, stress is concentrated at the notch, and the crack propagates along the notch tip. The WC grain boundary (grain size 0.5-1 μm) increases the propagation resistance by deflecting the crack path (deflection angle 20°-40°), and the Co phase absorbs energy through plastic deformation (strain 0.05%-0.1%).

Izod test mechanism:

In the cantilever beam force mode, the crack propagation path is affected by the shear stress and may extend along the WC-Co interface or through the grain. The plastic dissipation of the Co phase and the hindering effect of the WC grain boundary are similar to the Charpy test, but the shear stress makes the crack deflection more complicated.

Microscopic mechanism:

Co phase plastic dissipation: Co phase absorbs impact energy through plastic deformation and delays crack propagation. When the Co content is 10%, the strain rate is $\sim 10^{-3} s^{-1}$, and the plastic dissipation is significant.

WC 晶界阻碍: WC 晶界通过 Orowan 强化机制 ($\tau \sim Gb/\lambda$, $\lambda < 1 \mu m$) 阻碍裂纹扩展, 适中晶粒尺寸 (0.5-1 μm) 效果最佳。

Fracture

morphology: SEM analysis shows that the fracture is mainly composed of dimples (size $< 2 \mu m$), indicating that plastic fracture is dominant and plastic deformation of the Co phase is the main energy absorption mechanism.

Environmental impact:

Low temperature properties: At -40°C, the toughness of the Co phase decreases slightly, but the appropriate Co content (10%) still maintains impact toughness through plastic dissipation.

High strain rate: When the strain rate is $> 10^3 s^{-1}$, the crack growth rate increases (about 15%-20%) because the material does not have time to fully deform plastically.

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Analysis of influencing factors

Impact toughness is affected by the following factors:

Co content:

Effect: Increasing Co content (>10%) improves impact toughness due to its enhanced plastic deformation ability.

Mechanism: When the Co content is <6%, the material brittleness increases; when it is >15%, the hardness decreases, affecting the wear resistance.

Recommendation: Co content of 10%-12% is the balance point between toughness and hardness.

Grain size:

Function: Moderate grain size (0.5-1 μm) optimizes impact toughness.

Mechanism: Too fine grains (<0.2 μm) reduce toughness due to increased grain boundary defects; too coarse grains (>2 μm) reduce grain boundary density and reduce crack propagation resistance.

additive:

Function: Adding VC or TaC improves impact toughness.

Mechanism: VC (0.2%-0.5%) inhibits grain growth and strengthens grain boundaries; excessive amount (>0.8%) forms brittle phase and reduces toughness.

Notch Depth:

Effect: The notch depth increases and the stress concentration intensifies.

Mechanism: When the notch depth is >3 mm, the stress concentration factor increases and the impact toughness decreases.

Standard: 2 mm is the standard test depth.

Sintered density:

Function: High density improves impact toughness.

Mechanism: When the density is <98%, the porosity increases (>2%), and the pores become crack sources, reducing toughness.

Recommended: density >99%, porosity <1%.

Test temperature:

Effect: Low temperature reduces impact toughness.

Mechanism: When the temperature is less than -60°C, the toughness of the Co phase decreases significantly and the proportion of brittle fracture increases.

Strain rate:

Effect: High strain rate reduces impact toughness.

Mechanism: When the strain rate is $>10^{-3} \text{ s}^{-1}$, the material has insufficient time for plastic deformation and crack propagation is accelerated.

Optimization strategy

To improve the impact toughness of cemented carbide, the following strategies can be adopted:

Microstructure Optimization:

Co content is 10%-12%, WC grain size is 0.5-1 μm , balancing toughness and hardness.

Additive Control:

Adding 0.2%-0.5% VC or TaC can enhance grain boundary strength and improve impact toughness.

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Process control:

Sintered density >99%, porosity <1%, achieved by vacuum sintering (1400-1500°C, vacuum <10⁻² Pa).

Test accuracy:

The notch depth machining accuracy is ±0.02 mm and the pendulum energy deviation is <0.5 J.

Improved low temperature performance:

Adding Ni (1%-3%) as an auxiliary bonding phase enhances low-temperature toughness and maintains high impact toughness at -60°C.

Fractographic analysis:

by SEM (resolution <0.2 μm). The dimple size was <2 μm , indicating that plastic fracture was dominant.

Engineering application practice

High impact toughness cemented carbide performs well in a variety of scenarios:

Mining drill bits: WC-10Co (Co content 10%), with optimized microstructure to meet high-frequency impact requirements (>500 Hz).

Aviation tools: WC-8Co, suitable for dynamic loading in high-speed cutting (>800 m/min).

Wear-resistant die: WC-12Co, withstand high-frequency stamping (>10⁶ times).

Deep sea valve: WC-10Co, performs well in deep sea high pressure (>80 MPa) impact.

Wind turbine blade mold: WC-10Co (Ni 2%), stable at low temperature (-60°C) and high strain rate (>10³ s⁻¹).

Cemented Carbide Impact Toughness Test (Charpy and Izod) - Table Comparison

The following is a direct comparison of the Charpy and Izod impact toughness test methods in cemented carbide (WC-Co) in the form of a table, covering the concepts, specimen specifications, loading methods, stress distribution, test process, characteristics and applicability, micro-mechanisms and influencing factors.

project	Charpy impact test (ASTM E23)	Izod impact test (ASTM E23)
concept principle	The three-point bending loading method is adopted, and the pendulum impacts the specimen to measure the energy required for fracture (impact work). The specimen has a V-notch to simulate stress concentration and evaluate the fracture resistance.	The cantilever beam loading method is adopted, and the pendulum impacts the free end of the specimen to measure the fracture energy. The specimen is notched to evaluate the resistance to stress concentration and crack propagation.
Sample Specification	- Dimensions: 55 × 10 × 10 mm (length × width × height). - Notch: V-shaped, depth 2 mm, bottom radius 0.25 mm, angle 45°.	- Dimensions: 75 × 10 × 10 mm (length × width × height). - Notch: V-shaped, 2 mm deep, 0.25 mm bottom radius, 45° angle, about 22 mm from the clamping end .
load Way	The sample is placed horizontally on two fulcrums, and the pendulum strikes the center of the sample (the back of the notch) at a speed of 4-5 m/s, forming a three-point bending force.	One end of the sample is fixed to the fixture, and the other end is suspended to form a cantilever beam. The pendulum hits the free end of the sample (the back of the notch) at a speed of 4-5 m/s.

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project	Charpy impact test (ASTM E23)	Izod impact test (ASTM E23)
stress distributed	Tensile stress is generated at the notch, and the maximum tensile stress is concentrated at the bottom of the notch, with a stress concentration factor (K_t) of about 2-3. The impact energy is mainly contributed by the crack extension energy.	Tensile stress and shear stress are superimposed at the notch. The maximum tensile stress is located at the bottom of the notch, and the shear stress is distributed along the thickness. The stress concentration factor (K_t) is about 2.5-3.5.
test process	1. Process the specimen and the notch (accuracy ± 0.02 mm). 2. Place at a specified temperature (e.g. 20-25°C or -40°C). 3. Impact with a pendulum, record the height difference, and calculate the impact energy: $\text{Impact energy} = m \cdot g \cdot (h_{\text{initial}} - h_{\text{final}})$.	1. Process the specimen and the notch (accuracy ± 0.02 mm). 2. Fix one end of the specimen to ensure that it is not loose. 3. The pendulum strikes the free end, records the height difference, and calculates the impact energy (the formula is the same as Charpy).
Features applicability	- Simulates three-point bending stress (such as front impact of a drill). - Suitable for evaluating the fracture resistance of cemented carbide under symmetrical impact. - The results are greatly affected by notch geometry and temperature.	- Simulates cantilever beam forces (e.g. lateral impact on mechanical parts). - Suitable for evaluating the impact resistance of cemented carbide under complex stress states. - Results are sensitive to clamping conditions.
Micro mechanism	- Plastic dissipation of Co phase: Co phase absorbs energy through plastic deformation (strain 0.05%-0.1%), delaying crack propagation. - WC grain boundary hindrance: Grain boundaries (0.5-1 μm) increase resistance by deflecting cracks (angle 20°-40°). - Fracture morphology: Dimples (size $< 2 \mu\text{m}$) dominate, indicating plastic fracture.	- Plastic dissipation of Co phase: Similar to Charpy, Co phase absorbs energy plastically. - WC grain boundary obstruction: The crack path is more complicated and may extend along the WC-Co interface or through the grain under the influence of shear stress. - Fracture morphology: Mainly dimples, but shear stress may increase the proportion of intergranular fracture.
Influence factor	- Co content: 10%-12% balances toughness and hardness. - Grain size: 0.5-1 μm is optimal, too fine or too coarse reduces toughness. - Additives: VC (0.2%-0.5%) strengthens grain boundaries, excessive ($> 0.8\%$) forms brittle phases. - Notch depth: > 3 mm Stress concentration intensifies and reduces toughness. - Sintered density: $> 99\%$, porosity $< 1\%$. - Temperature: $< -60^\circ\text{C}$ Toughness decreases. - Strain rate: $> 10^{-3} \text{ s}^{-1}$ accelerates crack growth (about 15%-20%).	- Co content: same as Charpy, 10%-12% is good. - Grain size: 0.5-1 μm is the best. - Additives: VC (0.2%-0.5%) has the same effect. - Notch depth: > 3 mm reduces toughness. - Sintered density: $> 99\%$, porosity $< 1\%$. - Temperature: $< -60^\circ\text{C}$ reduces toughness. - Strain rate: $> 10^{-3} \text{ s}^{-1}$ accelerates crack growth, the effect is slightly greater than Charpy due to shear stress.

7.3 Analysis of cemented carbide failure mechanism

Cemented carbide is prone to wear failure (wear rate $> 0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$) and fracture spalling (crack length $> 0.05 \text{ mm}$) under harsh working conditions (high friction $> 800 \text{ MPa}$, impact $> 500 \text{ Hz}$, high temperature $> 800^\circ\text{C}$), leading to failure of aviation tools (life < 10 hours), mining drills (drilling $< 1000 \text{ m}$) and dies (extrusion $< 10^6$ times). Failure mechanism analysis reveals the cause of performance degradation through wear model (Archard formula), fracture mechanics (stress concentration factor $K_t > 1.5$) and advanced analysis techniques (such as X-ray micro-tomography),

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providing a basis for optimization.

This section discusses the failure mechanism from three aspects: wear failure (abrasive wear, adhesive wear), fracture and spalling (stress concentration and microcracks), and environmental influence (high temperature, corrosion). It combines microscopic analysis (SEM, X-ray micro-tomography), mechanical model ($K \propto 10^{-14} \text{ MPa} \cdot \text{m}^{1/2}$) and cases.

7.3.1 Wear failure of cemented carbide (abrasive wear, adhesive wear)

Wear failure principle and technology overview of

cemented carbide Wear failure is the main form of cemented carbide failure, including abrasive wear (hard particle cutting, wear rate $\sim 0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$) and adhesive wear (material transfer, wear depth $> 5 \mu\text{m}$). Abrasive wear is common in mining (rock hardness $> 800 \text{ HV}$), and adhesive wear is more common in cutting (temperature $> 600^\circ\text{C}$). Based on the Archard formula ($V = k \cdot F \cdot S / H$), optimization requires improving hardness (HV 1500) and surface quality ($R_a < 0.1 \mu\text{m}$).

Wear tests are based on a sand flow of 200-400 g/min and a load of 100-150 N. In recent years, X-ray micro-tomography (resolution $< 1 \mu\text{m}$) has become a research hotspot, which can reconstruct the wear scar morphology in three dimensions (groove width $< 10 \mu\text{m}$).

Wear failure mechanism and analysis of cemented carbide

Abrasive wear

Hard particles (SiO_2 , hardness $> 800 \text{ HV}$) cut WC (depth $0.5\text{-}2 \mu\text{m}$), forming grooves (width $5\text{-}15 \mu\text{m}$). When the hardness is HV 1500, the wear rate is $< 0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$; if the hardness is < 1200 , the wear rate increases by 20%-30%.

Adhesive wear

At high temperatures ($> 600^\circ\text{C}$), the Co phase softens (HV ~ 300) and material is transferred to the mating surface (thickness $2\text{-}5 \mu\text{m}$). WC grain size of $0.5 \mu\text{m}$ reduces adhesion (wear rate $< 0.12 \text{ mm}^3 / \text{N} \cdot \text{m}$).

High temperature wear

At 800°C , the wear rate is $< 0.15 \text{ mm}^3 / \text{N} \cdot \text{m}$ and an oxide layer (WO_3 , thickness $\sim 2 \mu\text{m}$) is formed, reducing wear by 5%-10%.

Corrosion and wear

In an acidic environment ($\text{pH} < 5$), the wear rate increases by 15%-20%, with the dissolution of the Co phase (rate $\sim 10^{-10} \text{ g/cm}^2 \cdot \text{s}$) being the main reason.

X-ray micro-tomography shows that abrasive wear is mainly grooved, and adhesive wear is accompanied by tear pits (diameter $\sim 5\text{-}10 \mu\text{m}$). For example, the wear rate of WC-10Co (grain $0.5 \mu\text{m}$) is $< 0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$, which meets the mining requirements.

Analysis of factors affecting wear failure

of cemented carbide Wear failure is affected by the following factors:

Hardness: When HV 1500, the wear rate is $< 0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$; if < 1200 , the wear rate increases by

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20%-30%.

Grain size: When it is $0.5-1\ \mu\text{m}$, the wear rate is low; if it is $>2\ \mu\text{m}$, the wear rate increases by 15%-20%.

Co content: When it is 10%, adhesive wear is less; if it is $>15\%$, the wear rate increases by 10%-15%.

Surface roughness: When $R_a < 0.1\ \mu\text{m}$, the wear rate is low; if $>0.2\ \mu\text{m}$, the wear rate increases by 20%-25%.

Operating temperature: $>600^\circ\text{C}$, adhesive wear increases by 40%-50%.

Abrasive particle size: When $<50\ \mu\text{m}$, the wear rate is $<0.1\ \text{mm}^3 / \text{N} \cdot \text{m}$; if $>100\ \mu\text{m}$, the wear rate increases by 30%-40%.

Environmental corrosion: When $\text{pH} < 5$, the wear rate increases by 15%-20%; if $\text{pH} > 7$, the wear rate changes by $< 5\%$.

reduce

the wear rate ($<0.1\ \text{mm}^3 / \text{N} \cdot \text{m}$), the following strategies are recommended:

The WC grain size is selected to be $0.5-1\ \mu\text{m}$ and the hardness is HV 1500.

Co content is 10% to reduce adhesive wear.

The surface is polished to $R_a < 0.1\ \mu\text{m}$, and the wear rate is reduced by 15%-20%.

Adding 0.2%-0.5% VC can increase the hardness by 3%-5%.

Using coolant (temperature $<500^\circ\text{C}$), adhesive wear is reduced by 20%-30%.

Cr_3C_2 (0.1 %-0.3%) under high temperature conditions forms a Cr_2O_3 layer (thickness $\sim 1\ \mu\text{m}$), and the wear rate decreases by 5%-10%.

Coating protection: Applying a CrN coating (thickness $2-4\ \mu\text{m}$, hardness HV 3000-3500) reduces the wear rate to $<0.08\ \text{mm}^3 / \text{N} \cdot \text{m}$.

Carbide Wear Failure Engineering Application Practice

Low-wear cemented carbide performs well:

Mining drill bit: WC-10Co (wear rate $<0.1\ \text{mm}^3 / \text{N} \cdot \text{m}$), drilling distance $>1200\ \text{m}$, an increase of 40%.

Aviation tools: WC-8Co (hardness HV 1500), low adhesive wear, life > 15 hours.

Wear-resistant die: WC-12Co ($R_a < 0.1\ \mu\text{m}$), wear rate $<0.12\ \text{mm}^3 / \text{N} \cdot \text{m}$, extrusion times $>10^6$ times.

Aviation turbine blades: WC-10Co (grain size $0.5\ \mu\text{m}$, CrN coating $3\ \mu\text{m}$), in high temperature wear ($>800^\circ\text{C}$), wear rate $<0.08\ \text{mm}^3 / \text{N} \cdot \text{m}$, life span >4000 hours, an increase of 40%.

7.3.2 Cemented Carbide Fracture and Spalling (Stress Concentration and Microcracks)

Principle and Technology Overview

Fracture and spalling are initiated by stress concentration ($K_t > 1.5$) and microcracks (length $>0.05\ \text{mm}$), which are common in aviation tools (cutting life <10 hours) and mining drill bits (drilling $<1000\ \text{m}$). Fracture is based on fracture mechanics (K_{Ic} $10-14\ \text{MPa} \cdot \text{m}^{1/2}$), and spalling involves interface failure (bonding strength $<40\ \text{MPa}$). Optimization requires increasing K_{Ic} and interface

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energy ($<1.5 \text{ J/m}^2$).

Failure analysis Cracks were detected by SEM (resolution $< 0.2 \mu\text{m}$), CT scanning (accuracy $\pm 0.02 \text{ mm}$) and acoustic emission technology (frequency range 20 kHz-500 kHz). For example, WC-10Co tools had a life of < 10 hours due to spalling caused by microcracks.

Mechanism and analysis

Fracture: Stress concentration (K_t is 1.8-2.0) triggers crack growth (rate 10^{-2} m/s), and fracture occurs when $K_{Ic} < 10 \text{ MPa}\cdot\text{m}^{1/2}$ (crack length $> 0.5 \text{ mm}$).

Spalling: Interfacial stress ($>80 \text{ MPa}$) causes tearing of the Co phase (depth $\sim 5\text{-}10 \mu\text{m}$), and the bonding strength is $<40 \text{ MPa}$.

Crack path: Transgranular fracture (WC grain rupture, size $0.5 \mu\text{m}$) and intergranular fracture (grain boundary peeling, width $0.05\text{-}0.1 \mu\text{m}$) coexist. When the crack deflection angle is $20^\circ\text{-}40^\circ$, the expansion rate decreases by 5%-10%.

Environmental impact: In a corrosive environment (NaCl concentration 3.5%), the crack growth rate increases by 20%-25%, and stress corrosion (SCC) is the main cause.

^{3} times in advance). For example, the fracture rate of WC-10Co ($K_{Ic} < 12 \text{ MPa}\cdot\text{m}^{1/2}$) is $<0.2\%$, which meets the tool requirements.

Analysis of influencing factors

Fracture and spalling are affected by the following factors:

K_{Ic} : When $K_{Ic} > 12 \text{ MPa}\cdot\text{m}^{1/2}$, the fracture rate is $<0.2\%$; if $<10 \text{ MPa}\cdot\text{m}^{1/2}$, the fracture rate increases by 40%-50%.

Grain size: When it is $0.5\text{-}1 \mu\text{m}$, the crack propagates slowly; if it is $>2 \mu\text{m}$, the fracture rate increases by 20%-30%.

Co content: When it is 10%, the peeling rate is less; if it is $<6\%$, the peeling rate increases by 15%-20%.

Surface defects: When the crack length is $>0.05 \text{ mm}$, the fracture rate increases by 40%-50%.

Stress concentration: When $K_t > 2$, the spalling rate increases by 30%-40%.

Environmental corrosion: When the NaCl concentration is $>3.5\%$, the crack growth rate increases by 20%-25%.

Temperature: At $>600^\circ\text{C}$, thermal stress ($>150 \text{ MPa}$) causes a 15%-20% increase in spalling rate.

Optimization strategy

To reduce fracture and spalling ($<0.2\%$), the following strategies are recommended:

The Co content is 10% and the WC grain size is $0.5\text{-}1 \mu\text{m}$ to make $K_{Ic} > 12 \text{ MPa}\cdot\text{m}^{1/2}$.

Adding 0.2%-0.5% VC can increase the grain boundary strength by 5%-10%.

The surface is polished to $Ra < 0.1 \mu\text{m}$, and crack initiation is reduced by 20%-25%.

Design the rounded corners (radius $> 0.5 \text{ mm}$) so that $K_t < 1.5$.

CT scanning (accuracy $\pm 0.02 \text{ mm}$) and acoustic emission (frequency range 20 kHz-500 kHz) were used to detect microcracks.

Corrosion protection: Application of Al_2O_3 coating (thickness $1\text{-}3 \mu\text{m}$, hardness HV 2500-3000) reduces the impact of stress corrosion and the fracture rate is reduced to $<0.1\%$.

Engineering application practice:

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cemented carbide with low fracture rate performs well:

Aviation tools: WC-10Co (K_{Ic} 12 MPa $\cdot$ m^{1/2}), fracture rate <0.2%, life>15 hours.

Mining drill bit: WC-8Co (stripping rate <0.2%), drilling distance >1200 m, an increase of 40%.

Wear-resistant mold: WC-12Co (K_t <1.5), extrusion times > 10⁶ times, increased by 25%.

PCB drill bit: WC-10Co (grain 0.5 μ m, Al₂O₃ coating 2 μ m), in high stress drilling (>10⁴ holes), the fracture rate is <0.1%, and the life span is >10⁵ holes, which is improved by 80%.

7.4. Strategies for improving cemented carbide performance

7.4.1 Cemented Carbide Performance Improvement Strategy - Cemented Carbide Grain Refinement

Overview of cemented carbide grain refinement principle and technology

Grain refinement of cemented carbide (WC-Co) is a microstructural optimization technology that precisely controls the grain size of tungsten carbide (WC) to less than 0.5 μ m. This process significantly improves the hardness and strength of the material, laying a solid foundation for the application of cemented carbide under harsh working conditions. Grain refinement relies on the Hall-Petch effect ($\sigma_y = \sigma_0 + k \cdot d^{-1/2}$), which indicates that as the grain size decreases, the grain boundary density increases significantly (up to >10¹³ m⁻²), thereby enhancing the material's resistance to plastic deformation and crack growth. This refinement technology is able to increase the hardness to HV 1600-1800 and the strength to over 4500 MPa, making cemented carbide excel in high-strength tools and wear-resistant components.

The core process to achieve grain refinement includes high-energy ball milling for 20-40 hours, using high-speed rotating grinding media (such as tungsten carbide balls) to mechanically crush and evenly mix the raw materials, followed by vacuum sintering (temperature range 1400-1500°C, vacuum degree strictly controlled at <10⁻² Pa) to ensure the stability of grain size and avoid excessive growth. In recent years, technological advances have promoted the introduction of multi-component additives (such as VC+TaC+ZrC) to further optimize the grain refinement effect. These additives are added at a low ratio of 0.1%-0.3%, which can maintain the grain size in the ultra-fine range of 0.2-0.5 μ m, thereby pushing the hardness to HV 1800-2000, while increasing the fracture toughness (K_{Ic}) to 13 MPa $\cdot$ m^{1/2}, providing more possibilities for high-end applications.

Mechanism and analysis of cemented carbide grain refinement

Grain refinement significantly enhances the mechanical properties of cemented carbide by reducing the WC grain size (<0.5 μ m). The mechanism can be deeply analyzed at the microscopic level:

Grain boundary strengthening

When the WC grain size is reduced to <0.5 μ m, the grain boundary density increases significantly (>10¹³ m⁻²). According to the Hall-Petch effect, the material hardness increases by 25%-30% (reaching HV 1600-1800) and the strength increases by about 20%-25%. This high-density grain

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boundary network effectively hinders dislocation movement and enhances the material's ability to resist deformation.

Orowan Enhancement

When the inter-grain spacing λ is reduced to $<0.5 \mu\text{m}$, the strengthening factor $\tau \sim Gb/\lambda$ (where G is the shear modulus and b is the Burgers vector) increases significantly, and dislocations are "stuck" at the grain boundaries, further improving the anti-slip ability. This mechanism is particularly prominent in fine grains.

Microscopic uniformity

The fine grains are evenly distributed, which reduces local stress concentration points, improves the balance between hardness and toughness, and makes the material less prone to brittle fracture under high stress.

Taking WC-10Co alloy as an example, by refining the grain size to $<0.5 \mu\text{m}$, the hardness can reach HV 1700 and the fracture toughness K_{IC} is about $12\text{-}13 \text{ MPa}\cdot\text{m}^{1/2}$. This combination of properties makes it particularly suitable for high-strength tools such as mining drill bits and aviation cutting tools.

Analysis of influencing factors

The effect of grain refinement is affected by a combination of process parameters and material composition, including:

Grain size

When the grain size is controlled at $<0.5 \mu\text{m}$, the hardness can exceed 1600 HV; however, if the grain size exceeds $1 \mu\text{m}$, the grain boundary density decreases, the hardness drops to $<1500 \text{ HV}$, and the performance advantage is gradually lost.

Ball milling time

High-energy ball milling for 20-40 hours can effectively refine the grain size to $<0.5 \mu\text{m}$; if the ball milling time is less than 15 hours, the grain size may exceed $1 \mu\text{m}$, resulting in unsatisfactory refinement effect.

Sintering temperature

The temperature range of $1400\text{-}1500^\circ\text{C}$ can keep the grains stable and avoid excessive growth; if the temperature exceeds 1550°C , the grains may grow to $>1 \mu\text{m}$, and the performance will decrease.

Co content

When the Co content is 10%, the fracture toughness K_{IC} can reach $>12 \text{ MPa}\cdot\text{m}^{1/2}$, providing sufficient plastic buffer; if the Co content is lower than 6%, the toughness decreases significantly ($K_{IC} < 10 \text{ MPa}\cdot\text{m}^{1/2}$), limiting the application range of the material.

Optimization strategy

To achieve the high performance targets (hardness HV 1700, fracture toughness $K_{IC} > 12 \text{ MPa}\cdot\text{m}^{1/2}$), the following optimization strategies are recommended:

The WC grain size $<0.5 \mu\text{m}$ was selected and achieved by high-energy ball milling for 20-40 hours

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to ensure that the raw materials were fully crushed and evenly mixed.

The sintering temperature is strictly controlled at 1400-1500°C and the vacuum is maintained at $<10^{-2}$ Pa to prevent grain growth and oxidation reaction.

The Co content is maintained at 10%, and the balance between toughness and hardness is optimized by adjusting the ratio.

using a laser particle size analyzer (measurement deviation $<0.02\ \mu\text{m}$) to ensure uniform distribution and avoid local oversized grains affecting performance.

Engineering application practice

Grain-refined cemented carbide exhibits excellent performance in a variety of engineering applications:

Mining drill bits

WC-10Co (grain size $<0.5\ \mu\text{m}$), with a hardness of HV 1700, can significantly extend the drilling distance to $>1500\ \text{m}$, a 50% increase over traditional processes, effectively improving mining efficiency.

Aviation tools

WC-8Co (grain size $<0.5\ \mu\text{m}$), through grain refinement, the service life is extended to >15 hours, an increase of 25%, meeting the needs of high-precision cutting.

Wear-resistant mold

WC-12Co (grain size $<0.5\ \mu\text{m}$), extrusion times exceed 10^6 times, performance improvement of 25%, suitable for high-frequency stamping operations.

7.4.2 Strategies for Improving Cemented Carbide Performance, Cemented Carbide Additives (VC, TaC)

Principle and technical overview

The performance of cemented carbide is improved by introducing additives (such as VC, TaC) to optimize the microstructure, significantly enhance the grain boundary strength and inhibit the growth of WC grains, thereby improving the comprehensive performance of the material. The addition amount of VC and TaC is usually controlled at 0.2%-0.5%. Through solid solution strengthening and grain boundary modification, the hardness is increased to HV 1600-1800 and the fracture toughness (K_{IC}) is increased to $10-14\ \text{MPa}\cdot\text{m}^{1/2}$. The process flow includes high-energy ball milling to evenly mix the additives with the raw materials, and then solidify them in a vacuum sintering environment at 1400-1500°C. In recent years, the development of multi-additives (such as VC+TaC+ZrC, with a ratio of 0.1%-0.3%) has become a research hotspot. The synergistic effect of these additives pushes the hardness to HV 1800-2000 and K_{IC} to $13\ \text{MPa}\cdot\text{m}^{1/2}$, providing new possibilities for the application of cemented carbide under extreme working conditions.

Mechanism and analysis

Additives improve cemented carbide performance through the following specific mechanisms:

VC Add

Adding 0.2%-0.5% VC will form VCx phase (thickness $<20\ \text{nm}$) at the grain boundary, which can

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increase the hardness by about 10%-15% by inhibiting the growth of WC grains (growth rate $<10^{-10}$ m/s) while maintaining the stability of the microstructure.

TaC addition

Adding 0.2%-0.5% TaC significantly enhances the grain boundary strength (>150 MPa) and increases the fracture toughness K_{Ic} by 5%-10% through solid solution strengthening, effectively improving the material's resistance to crack growth.

Multi-additives

VC+TaC+ZrC (total ratio 0.1%-0.3%) can achieve an additional 3%-5% increase in hardness through solid solution strengthening with a grain boundary spacing of $<0.2 \mu\text{m}$, and K_{Ic} reaches $13 \text{ MPa} \cdot \text{m}^{1/2}$, achieving dual optimization of hardness and toughness.

Mechanical model

Combined with Orowan strengthening ($\tau \sim Gb/\lambda$) and grain boundary strengthening, dislocation movement is effectively hindered and deformation resistance is significantly enhanced. For example, after adding VC+TaC 0.3%, the hardness of WC-10Co alloy reaches HV 1700 and K_{Ic} is $13 \text{ MPa} \cdot \text{m}^{1/2}$, which meets the requirements of high-performance drill bits.

Analysis of influencing factors

The impact of additives on performance improvement is limited by many factors:

Additive content

VC and TaC is 0.2%-0.5%, and the performance is optimal within this range; if it exceeds 0.8%, the brittle phase ratio may exceed 0.5%, resulting in a decrease in toughness.

Multi-additive ratio

VC:TaC:ZrC = 1:1:1, the hardness increase is the largest (>1800); if the ratio is unbalanced (such as 1:2:1), the brittle phase ratio may exceed 1%, affecting the stability of the material.

Ball milling time

20-40 hours of ball milling ensures that the additives are evenly distributed; if less than 15 hours, the additives are unevenly dispersed and the effect is limited.

Sintering temperature

1400-1500°C maintains the chemical stability and grain boundary strengthening effect of the additive; if it exceeds 1550°C, the additive may volatilize or have side reactions, resulting in performance degradation.

Optimization strategy

To achieve the high performance targets (hardness HV 1700, fracture toughness K_{Ic} $13 \text{ MPa} \cdot \text{m}^{1/2}$), the following optimization strategies are recommended:

Adding VC/ TaC / ZrC (total ratio 0.1%-0.3%, ratio 1:1:1) can increase the hardness by 3%-5% through solid solution strengthening.

High-energy ball milling lasts for 20-40 hours to ensure that the additives and raw materials are fully mixed and evenly distributed.

The sintering temperature is controlled at 1400-1500°C and the vacuum degree is $<10^{-2}$ Pa to prevent the volatilization of additives.

Transmission electron microscopy (TEM, resolution $<0.1 \text{ nm}$) was used to verify the grain boundary

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modification effect and ensure the microscopic distribution of the additives.

Engineering application practice

Additive-optimized cemented carbides excel in engineering applications:

Mining drill bits

WC-10Co (VC+TaC 0.3%), with a hardness of HV 1700, can extend the drilling distance to >1500 m, an increase of 50%, significantly improving mining efficiency.

Aviation tools

WC-8Co (TaC 0.3%), life extended to >15 hours, an increase of 25%, to meet high-precision cutting needs.

New energy electrolyzer

WC-10Co (VC+TaC+ZrC 0.2%), with a hardness exceeding 1800, has a service life of >10³ hours under electrochemical shock (>10³ times) , an increase of 40%.

7.4.3 Strategies for Improving Cemented Carbide Performance and Strengthening Cemented Carbide Surface

Overview of Principles and Technologies of Cemented Carbide Surface Strengthening

significantly improves surface hardness and wear resistance through methods such as carburizing, ion implantation and laser cladding , which provides a guarantee for the long-term use of cemented carbide in high wear and dynamic loading environments. The carburizing process forms a WC-rich layer (thickness 10-30 μm, hardness>2000) in a CH₄ atmosphere at 850-950 °C, ion implantation introduces residual compressive stress (>400 MPa) through N⁺ ions (dose 10¹⁶-10¹⁷cm⁻² , energy 80-120 keV), and laser cladding uses 1.5-2.5 kW of laser power to generate a high hardness layer (thickness 50-100 μm , hardness>2500). These technologies together reduce the wear rate to <0.08 mm³ / N · m . In recent years, plasma enhanced ion implantation (PIII, dose 10¹⁷ -10¹⁸ cm⁻²) has become a research hotspot. Its deep strengthening effect can reach >0.5 μm , significantly improving surface durability.

Mechanism and analysis of cemented carbide surface strengthening

The specific mechanism of surface strengthening is as follows:

carburization

Carbon atoms diffuse (diffusion rate ~10⁻¹¹ cm² /s) to form a WC-rich layer (thickness 10-30 μm) on the surface with a hardness exceeding 2000 HV. The wear rate is reduced to <0.08 mm³ / N · m , effectively enhancing the surface wear resistance.

Ion implantation

The N⁺ ion implantation depth is 0.1-0.3 μm , forming a solid solution strengthened structure with residual compressive stress >400 MPa, increasing the fracture toughness K_{1c} by 5 %-10% and improving the surface crack growth resistance.

Laser Cladding

By melting the surface material with a laser power of 1.5-2.5 kW, a high-hardness layer

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(hardness>2500) with a thickness of 50-100 μm is formed, and the wear rate is further reduced to $<0.07 \text{ mm}^3 / \text{N} \cdot \text{m}$, while fatigue resistance is improved. For example, the hardness of WC-10Co alloy reaches HV 2000 and the wear rate is $<0.08 \text{ mm}^3/\text{N} \cdot \text{m}$ under the condition of a carburized layer of 20 μm , which fully meets the high performance requirements of aviation tools.

Analysis of factors affecting cemented carbide surface strengthening

The surface strengthening effect is affected by various process parameters and material properties:

Carburizing temperature

At 850-950°C, the carbon layer thickness is stable at 10-30 μm ; if the temperature exceeds 1000°C, the carbon layer may be too thick ($>50 \mu\text{m}$), resulting in an increased risk of spalling.

Ion implantation dose

10^{16} and 10^{17} cm^{-2} , the residual stress is $>400 \text{ MPa}$. If the dose exceeds 10^{18} cm^{-2} , the surface damage rate may rise to $>5\%$, affecting the service life.

Laser power

At 1.5-2.5 kW, the cladding layer is uniform and dense; if the power exceeds 3 kW, the thermal stress may exceed 200 MPa, causing microcracks.

Grain size

the grain size is $<0.5 \mu\text{m}$, the surface strengthening effect is the best; if it is $>2 \mu\text{m}$, the hardness increase is less than 10% and the strengthening efficiency is reduced.

Surface roughness

$R_a < 0.1 \mu\text{m}$, the strengthening layer is tightly bonded to the substrate; if $>0.2 \mu\text{m}$, the wear rate may increase by 15%-20%.

Optimization strategy for cemented carbide surface strengthening

To achieve the high hardness and wear resistance targets (hardness HV 2000, wear rate $<0.08 \text{ mm}^3 / \text{N} \cdot \text{m}$), the following optimization strategies are recommended:

The carburizing temperature is controlled at 850-950°C and the carbon layer thickness is precisely maintained at 10-30 μm to ensure uniform surface hardening.

The ion implantation dose was set at 10^{16} - 10^{17} cm^{-2} and energy at 80-120 keV to generate stable residual compressive stress.

The laser cladding power was adjusted to 1.5-2.5 kW, and the cladding layer thickness was controlled at 50-100 μm .

Select WC with grain size $<0.5 \mu\text{m}$ and polish the surface to $R_a < 0.1 \mu\text{m}$ to reduce wear sources.

using X-ray diffraction analysis (resolution $<1 \mu\text{m}$) to ensure consistent stress distribution and thickness.

Practice of cemented carbide surface strengthening engineering application

Surface-hardened cemented carbide performs well in engineering applications:

Aviation tools

WC-10Co (carburized layer 20 μm), hardness reaches HV 2000, life is extended to >15 hours, an increase of 25%, meeting the needs of high-precision cutting.

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Mining drill bits

WC-8Co (ion implanted $N^+ 10^{17} \text{ cm}^{-2}$), wear rate $<0.08 \text{ mm}^3 / \text{N} \cdot \text{m}$, drilling distance exceeds 1500 m, an increase of 50%, significantly improving mining efficiency.

Wear-resistant mold

WC-12Co (laser cladding layer $80 \mu\text{m}$), hardness >2500 , extrusion times more than 10^6 times, an increase of 25%, suitable for high-frequency stamping operations.

7.4.4 Cemented Carbide Performance Improvement Strategy - Cemented Carbide Advanced Manufacturing Technology (3D Printing)

Principle and technical overview of cemented carbide advanced manufacturing technology

and selective laser melting (SLM) or binder jet molding process is used to precisely control the material distribution to optimize hardness (HV 1500-1800), toughness (K_{1c} 10-14 $\text{MPa} \cdot \text{m}^{1/2}$) and fatigue resistance ($>10^5$ times). The SLM process uses 200-300 W laser power and a layer thickness of $20-50 \mu\text{m}$. The binder jet molding technology achieves high-resolution ($<50 \mu\text{m}$) printing through binder jetting. In recent years, nano 3D printing technology (layer thickness $<10 \mu\text{m}$) has become a cutting-edge hotspot, capable of manufacturing high - precision gradient structures, with hardness increased to >1800 and K_{1c} exceeding $13 \text{ MPa} \cdot \text{m}^{1/2}$, providing a new path for the design of complex components.

Mechanism and analysis of advanced manufacturing technology of cemented carbide

Mechanisms by which 3D printing improves performance include:

Gradient structure

By adjusting the material distribution, high hardness is achieved on the surface (HV >1800) while high toughness is maintained inside ($K_{1c} >13 \text{ MPa} \cdot \text{m}^{1/2}$), effectively reducing stress concentration and improving overall reliability.

Micro-control

Layer thickness $<50 \mu\text{m}$ ensures density $>99\%$, porosity is reduced to $<0.5\%$, and the material's resistance to crack growth is enhanced.

Heat treatment effect

Post-treatment temperature of $800-1000^\circ\text{C}$ eliminates residual stress ($<100 \text{ MPa}$), further improving fatigue resistance and structural stability.

For example, WC-10Co alloy prepared by SLM has a hardness of HV 1700, K_{1c} $12 \text{ MPa} \cdot \text{m}^{1/2}$, and a fatigue life of more than 10^5 times, showing excellent comprehensive performance.

Analysis of factors affecting cemented carbide advanced manufacturing technology

3D printing results are affected by a variety of process parameters:

Laser power

At 200-300 W, the molten pool is formed stably and the materials are fused evenly; if it exceeds 350 W, the thermal stress may reach $>150 \text{ MPa}$, affecting the quality of the parts.

Layer thickness

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20-50 μm , the density is >99%; if the layer thickness exceeds 100 μm , the porosity may rise to >1%, reducing the performance.

Print speed

10-20 mm/s ensures the interlayer bonding strength; if the speed exceeds 30 mm/s, the interlayer bonding force decreases, affecting the overall strength.

Post-processing temperature

800-1000°C optimizes the microstructure; if it exceeds 1100°C, the grains may grow and the performance may degrade.

Optimization strategy of cemented carbide advanced manufacturing technology

To achieve the high performance targets (hardness HV 1700, fracture toughness $K_{IC} > 12 \text{ MPa} \cdot \text{m}^{1/2}$), the following optimization strategies are recommended:

The laser power was controlled at 200-300 W and the layer thickness was set to 20-50 μm to ensure the stability and density of the molten pool.

The printing speed was maintained at 10-20 mm/s, and the post-processing temperature was 800-1000°C to eliminate residual stress.

Optimize the Co content to 10% to improve the balance between toughness and hardness.

Use computed tomography (CT, resolution <10 μm) to detect internal defects and ensure print quality.

Engineering application practice of advanced manufacturing technology of cemented carbide

3D printed carbide excels in engineering applications:

Aviation tools

WC-8Co (SLM process), hardness HV 1700, life extended to >15 hours, an increase of 25%, to meet high-precision processing needs.

Wear-resistant mold

WC-12Co (binder jetting process), extrusion times exceed 10^6 times, an increase of 25%, suitable for complex shape molds.

Complex parts

WC-10Co (nano 3D printing), fracture toughness $K_{IC} > 13 \text{ MPa} \cdot \text{m}^{1/2}$, fatigue life > 10^5 times, an increase of 30%, suitable for customized high-performance components.

7.5 Future Development Trends: Application of AI+IIoT in Cemented Carbide Performance Optimization

artificial intelligence (AI) and industrial Internet of Things (IIoT) has brought revolutionary changes to the performance optimization and industrial application of cemented carbide (WC-Co). Through the data-driven modeling capabilities of AI and the real-time perception and control capabilities of IIoT, cemented carbide has achieved intelligent upgrades in microstructure design, performance monitoring, failure prediction, and process optimization. The following systematically discusses the application prospects of AI+IIoT in cemented carbide performance optimization from four dimensions: microstructure optimization, real-time performance monitoring, failure prediction

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and intelligent maintenance, process optimization and intelligent manufacturing, combined with the latest research and data.

7.5.1 Microstructure Optimization: AI-Driven Precision Design

AI technology, through algorithms such as machine learning (ML), deep learning (DL) and reinforcement learning (RL), combined with big data analysis, can accurately predict the complex relationship between cemented carbide microstructure parameters (such as grain size, Co content, additive ratio) and performance (hardness, toughness), thereby achieving optimal design of the microstructure.

Grain size optimization

AI algorithms such as support vector machines (SVM) and deep neural networks (DNN) can predict the effect of grain size on hardness based on historical process data (e.g., ball milling time, sintering temperature), with a prediction accuracy of 92%-96% (Fraunhofer Institute, Germany, 2024).

In 2024, the Fraunhofer Institute in Germany developed an AI grain optimization system based on digital twins. By simulating the WC-Co microstructure (Monte Carlo method), the grain size deviation was controlled to $\pm 0.01 \mu\text{m}$, and the hardness consistency was improved by 12%-15% (HV 1650-1800). For example, when the grain size was optimized from $0.5 \mu\text{m}$ to $0.3 \mu\text{m}$, the hardness increased by 10% (HV 1700 to 1870), and the toughness (K_{IC}) was maintained at 12-13 $\text{MPa}\cdot\text{m}^{1/2}$ (Vickers hardness tester and single-edge notched beam method test).

Optimization of Co content and distribution

In 2024, the Massachusetts Institute of Technology (MIT) developed an AI-assisted Co content optimization system, which combined Bayesian optimization and Monte Carlo simulation to control the Co distribution deviation to $< 0.1\%$ (X-ray fluorescence spectroscopy analysis), and improved performance consistency by 15%-18%.

Through reinforcement learning (RL), AI dynamically adjusts the Co content (6%-10%), controls the fracture toughness (K_{IC}) deviation to $< 0.4 \text{ MPa}\cdot\text{m}^{1/2}$, and improves the toughness consistency (K_{IC} 20%, test range 12-14 $\text{MPa}\cdot\text{m}^{1/2}$). After optimization, the hardness of WC-10Co cemented carbide is stabilized at HV 1680-1750, and the toughness is improved by 10% (K_{IC} from 12.5 to 13.8 $\text{MPa}\cdot\text{m}^{1/2}$).

Optimization of additive ratio

the effect of the ratio of additives (such as VC, TaC) on performance through the gradient boosting tree (GBDT) algorithm, optimizes the VC addition (0.2%-0.4%) with an accuracy of 95%, and increases the hardness by 5%-8% (HV 1750-1850). In 2025, a study by Uppsala University in Sweden showed that after AI optimized the VC+TaC ratio (1:1, 0.3% total addition), the grain growth rate decreased by 6% ($< 10^{-9} \text{ m/s}$, TEM measurement), and the hardness reached HV 1900-1950.

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7.5.2 Real-time performance monitoring: high-precision perception of IIoT

IIoT enables real-time monitoring of cemented carbide performance parameters through embedded sensors, edge computing and 5G networks, ensuring process stability and performance consistency.

Key parameter monitoring

Grain size

The laser nanoparticle size analyzer (accuracy $\pm 0.005 \mu\text{m}$) monitors the change of grain size in real time, and the deviation is controlled at $< 0.01 \mu\text{m}$ (RWTH Aachen University, Germany, 2024).

Co content

An X-ray meta-analysis sensor (accuracy $\pm 0.05\%$) monitors the Co diffusion rate ($< 10^{-10} \text{ cm}^2/\text{s}$) and ensures distribution homogeneity (deviation $< 0.3\%$).

Stress distribution

Strain sensors (accuracy $\pm 0.5 \text{ MPa}$) monitor thermal stress changes with a ΔK_{IC} deviation of $< 0.4 \text{ MPa} \cdot \text{m}^{1/2}$ and a hardness fluctuation of $< \pm 1.8\%$ (HV 1650-1680).

Dynamic process adjustment

IIoT transmits real-time data to the cloud platform via the 5G network (delay $< 5 \text{ ms}$), and combines with AI algorithms to dynamically adjust the ball milling time (deviation $\pm 0.3 \text{ hours}$) and sintering temperature (deviation $\pm 3^\circ\text{C}$). For example, the grain size deviation is reduced from $0.05 \mu\text{m}$ to $0.02 \mu\text{m}$, and the performance consistency is improved by 15% (hardness deviation $< 0.5\%$).

Surface Enhancement Monitoring

laser cladding process, IIoT uses infrared temperature sensors (accuracy $\pm 1.5^\circ\text{C}$) to monitor thermal stress changes (deviation $< 8 \text{ MPa}$) and optimize the quality of the cladding layer. In 2024, RWTH Aachen University in Germany developed an AI+IIoT The laser cladding system adjusts the laser power (1.5-2.5 kW) in real time to increase the hardness of the cladding layer to HV 2600-2700, with a thickness deviation of $< 5 \mu\text{m}$ (SEM measurement).

7.5.3 Failure Prediction and Intelligent Maintenance: Collaborative Application of AI+IIoT

AI and IIoT significantly improves the failure prediction and intelligent maintenance capabilities of cemented carbide, extending its service life and reducing failure rate.

Crack Growth and Fatigue Failure Prediction

AI uses recurrent neural networks (RNN) to predict crack growth rate (da/dN) with an accuracy of $> 92\%$ (University of Tokyo, Japan, 2024).

IIoT is equipped with acoustic emission sensors (frequency accuracy $\pm 1.5 \text{ kHz}$) to monitor crack initiation signals in real time (advance $> 10^3$ times) via 5G network.

In 2024, the University of Tokyo in Japan developed an AI fatigue life prediction system that predicts the crack growth rate (accuracy $\pm 10^{-10} \text{ mm/cycle}$), increasing the life of mining drill bits by 15%-20% (from 1500 m to 1800 m drilling distance).

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The failure rate has been reduced from 0.15% to <0.08% (field test data).

Impact toughness prediction

In 2024, Lund University in Sweden developed an AI prediction system that combines finite element analysis (FEA) and neural networks (NN) to predict impact toughness (K_{IC}) with an accuracy of $\pm 0.2 \text{ MPa} \cdot \text{m}^{1/2}$. After optimization, the impact resistance of mining drill bits increased by 22% (K_{IC} from 12.0 to 14.6 $\text{MPa} \cdot \text{m}^{1/2}$) and the service life was extended by 20%-25% (field test).

Wear failure prediction

improves the wear resistance of mining drill bits by 20%-25% by real-time monitoring of wear scar morphology (groove width prediction accuracy $\pm 0.4 \mu\text{m}$, measured under a microscope). The wear rate is reduced from $0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$ to $0.075 \text{ mm}^3 / \text{N} \cdot \text{m}$ (ASTM G65 test).

Crack Detection and Failure Time Prediction

In 2024, the University of Cambridge in the UK developed an AI crack detection system that combines acoustic emission (AE) and CT data (resolution $< 5 \mu\text{m}$) to improve failure prediction accuracy to ± 0.8 hours. The prediction lead time was increased from 10^3 times to 10^4 times, reducing the unexpected downtime rate by 30% (industrial application data).

7.5.4 Process Optimization and Intelligent Manufacturing: Efficient Collaboration of AI+IIoT

AI and IIoT in cemented carbide manufacturing has significantly improved process efficiency, performance stability and production intelligence.

Optimization of additive ratio

AI uses genetic algorithms (GA) to optimize the ratio of VC/ TaC / ZrC additives (total addition 0.1%-0.3%) with an error of <0.04% and a hardness consistency deviation of <1.5% (Seoul National University, South Korea, 2024). In 2024, Seoul National University in South Korea developed an AI additive optimization system that increases the hardness to HV 1900-2000 and maintains toughness at K_{IC} 12-13 $\text{MPa} \cdot \text{m}^{1/2}$ by real-time monitoring of grain growth rate ($< 10^{-10} \text{ m/s}$, TEM measurement).

Process parameter optimization

IIoT uses sensors (grain size accuracy $\pm 0.004 \mu\text{m}$) to monitor the ball milling and sintering process in real time, and AI adjusts parameters such as ball milling time (20-40 hours, deviation ± 0.4 hours) and sintering temperature (1400-1450°C, deviation $\pm 2^\circ\text{C}$) through a gradient descent algorithm. Production efficiency increased by 18%-22% (single batch output increased from 100 pieces to 120 pieces/hour, industrial data).

Surface Enhancement Optimization

AI predicts carburized layer thickness ($10\text{-}30 \mu\text{m}$, error $< 4 \mu\text{m}$) and ion implantation dose ($10^{16}\text{-}10^{17} \text{ cm}^{-2}$, error <5%), and hardness consistency is improved to <1.8% (HV 2000-2500). IIoT monitors carburized temperature in real time (850-950°C, deviation $\pm 1.5^\circ\text{C}$) to optimize carburized

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layer quality.

Quality inspection and intelligent maintenance

AI+IIoT uses surface performance data (hardness, wear rate) to achieve automated quality inspection, with a pass rate of 98.5% (industrial data). AI predicts failure time (error < 4 hours), and IIoT optimizes maintenance strategies, reducing downtime by 32%-35% and accident rates by 30%-35% (field testing).

7.5.5 The First Year of AI in China's Tungsten Industry

2025 was first defined by CTIA GROUP LTD as the "first year of AI in China's tungsten industry", marking a new stage in which China's cemented carbide industry is fully moving towards intelligent manufacturing. This concept not only reflects the in-depth application of AI and Industrial Internet of Things (IIoT) technologies in the tungsten industry , but also highlights China's strategic goal of leading technology in the global cemented carbide industry. The following is a detailed description of the significance of the practical significance, high entropy of cemented carbide, and the significance of cemented carbide grade batching.

7.5.5.1 The practical significance of the concept of “the first year of AI in China's tungsten industry”

CTIA GROUP LTD first proposed the concept of "2025 is the first year of AI in China's tungsten industry" on January 3, 2025 , reflecting the technological transformation needs and competitive pressure of China's tungsten industry in the global cemented carbide market.

Industry upgrading needs

China is the world's largest cemented carbide producer, accounting for more than 60% of global production in 2024 (data from the China Tungsten Industry Association), but has long relied on traditional manufacturing processes (such as pressing and sintering), and there is a gap in production efficiency and performance consistency with European and American countries (such as Sandvik and Kennametal) (hardness consistency deviation 5%-8% vs. 2%-3%). The introduction of AI+IIoT optimizes process parameters (such as sintering temperature deviation $\pm 2^{\circ}\text{C}$) through data-driven, increasing production efficiency by 18%-22% (single batch output increased from 100 pieces to 120 pieces/hour), and reducing hardness consistency deviation to <2%, narrowing the gap with the international advanced level.

Technology autonomy

In the past, China's cemented carbide manufacturing relied on imported equipment and technology (such as Germany's laser cladding system). In 2025, CTIA GROUP LTD and Tsinghua University jointly developed a domestic AI optimization system, which optimized the additive ratio (VC/ TaC ratio 1:1, error <0.03%) through genetic algorithm (GA), and the hardness was increased to HV 1950-2000, achieving independent control of technology. The proposal of the first year of AI marks China's transformation from a technology follower to a leader. The application ratio of domestic

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equipment is expected to increase from 40% in 2024 to 65% in 2026 (industry forecast).

Improved global competitiveness

AI+IIoT promotes the optimization of cemented carbide performance (such as K_{1c} increased to 13-15 $\text{MPa}\cdot\text{m}^{1/2}$), making Chinese cemented carbide products more competitive in the fields of aerospace (such as aviation tools) and mining (drill life increased by 20%). In 2025, China's cemented carbide exports are expected to increase by 15% (about US\$5 billion, predicted by the Ministry of Commerce), further consolidating its global market position.

7.5.5.2 Significance of high entropy treatment of cemented carbide

High-Entropy Hardmetals proposed by CTIA GROUP LTD refers to the formation of high-entropy alloy (HEA)-based hardmetals by introducing multiple elements (such as W, Ti, Ta, Nb, Cr) to improve the diversity and stability of performance.

Performance breakthrough

There is a contradiction between the hardness and toughness of traditional WC-Co cemented carbide (when the hardness is HV 1800, K_{1c} is usually $<10 \text{ MPa}\cdot\text{m}^{1/2}$). High entropy significantly improves the overall performance through the synergistic effect of multiple elements. In 2025, CTIA GROUP LTD plans to develop a high entropy cemented carbide (W-Ti-Ta-Nb-Co) with a hardness of HV 2100-2200 and a toughness of K_{1c} 14-16 $\text{MPa}\cdot\text{m}^{1/2}$ (single-side notched beam method test), which is 20%-30% higher than traditional WC-Co.

Microstructure Optimization

High entropy treatment uses AI algorithms (such as deep learning, DL) to predict the element ratio (W:Ti-Ta:Nb=1:1:1:1, error $<0.05\%$), forming a uniform high entropy phase (grain size 0.3-0.5 μm , TEM measurement), reducing grain boundary defects ($<0.1\%$). The grain boundary bonding strength is increased by 25% ($>180 \text{ MPa}$, nanoindentation test), and the fatigue resistance is significantly enhanced (lifespan $>1.5 \times 10^5$ times, rotary bending fatigue test).

Application Development

High entropy cemented carbide has excellent high temperature resistance (hardness $> \text{HV } 1800$ at 800°C), suitable for cutting tools for aircraft engine turbine blades, with a lifespan increase of 30% (from 12 hours to 15.6 hours, field test). Corrosion resistance is increased by 20% (acidic environment pH <4 , corrosion rate $<0.05 \text{ mm/year}$, electrochemical test), suitable for deep-sea mining equipment.

7.5.5.3 The significance of carbide grade batching

The cemented carbide grade batching proposed by CTIA GROUP LTD refers to the digital management of cemented carbide products throughout their life cycle through AI+IIoT technology, establishing a grade batch number database, and achieving performance traceability and customized production.

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Performance traceability

Each batch of cemented carbide products records production parameters (such as sintering temperature 1400°C, Co content 10%) through IIoT sensors, generates a unique batch number, and stores it on the cloud platform (data capacity>1TB, 2025). Users can query performance data (such as hardness HV 1750, $K_{IC} > 13 \text{ MPa} \cdot \text{m}^{1/2}$) through the batch number to ensure performance consistency (deviation <1.5%).

Customized production

automatically adjusts the grade formula (such as WC-12Co+0.3% TaC) according to customer needs (such as mining drill bits need $K_{IC} > 14 \text{ MPa} \cdot \text{m}^{1/2}$), shortening the production cycle by 25% (from 8 days to 6 days). Batch numbering supports small batch customization to meet the diverse needs of aerospace (high-toughness tools) and new energy (battery molds).

Quality management improvement

Brand batching uses AI to analyze historical data (>100,000 batches), identify abnormal processes (such as grain size deviation >0.02 μm), optimize parameters, and significantly improve the pass rate. Failure analysis efficiency is improved by 30%, and batch number traceability can quickly locate problem batches (<1 hour), reducing recall costs by 20%-25%.

7.5.6 Future Prospects and Challenges of Improving Cemented Carbide Performance

Future Prospects for Cemented Carbide Performance Improvement

Intelligent Manufacturing

AI+IIoT will further promote the transformation of cemented carbide manufacturing to smart factories, and production efficiency is expected to increase by 30%-40% in 2027 (McKinsey forecast).

Multi-material optimization

AI can predict the performance of multiphase composite cemented carbides (such as WC-Co-TiC), with hardness expected to exceed HV 2000 and toughness reaching $K_{IC} > 15 \text{ MPa} \cdot \text{m}^{1/2}$.

Full life cycle management

IIoT will enable performance tracking from raw materials to applications, and increase failure prediction to 10^5 times in advance.

Challenges of Improving Carbide Performance

Data quality

AI models rely on high-quality data. Current industrial data has high noise (deviation > 10%) and sensor accuracy needs to be improved.

cost

IIoT devices (sensors, 5G modules) are expensive to deploy and have a low ROI in the short term (<5%).

Security

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5G network transmission has the risk of data leakage, and encryption technology needs to be strengthened (AES-256 standard).

AI+IIoT provides a new path for optimizing cemented carbide performance. Through microstructure optimization (grain size deviation $<0.01\ \mu\text{m}$, hardness consistency improved by 15%), real-time performance monitoring (hardness deviation $<1.8\%$), failure prediction (advance amount $>10^4$ times, failure rate $<0.08\%$) and process optimization (production efficiency improved by 18%-22%), the performance consistency, reliability and production efficiency of cemented carbide are significantly improved. In the future, AI+IIoT will further promote the development of cemented carbide manufacturing towards intelligent and full life cycle management, and provide more efficient and reliable solutions for aviation, mining, new energy and other fields.

7.6 Relevant domestic and international standards

The following are domestic and international standards related to the mechanical properties of cemented carbide, covering Chinese, ISO, American and European standards, to ensure that readers can fully understand the test and evaluation basis:

related to mechanical properties of cemented carbide :

for properties of cemented carbide": specifies the test methods for hardness (HV), fracture toughness (K_{Ic}) and compressive strength.

GB/T 3849-2008 Test method for Vickers hardness of cemented carbide: Applicable to hardness testing (HV 1200-2000).

GB/T 7997-2010 Test method for fracture toughness of cemented carbide: Based on the single edge notched beam method (SENB) to test K_{Ic} .

GB/T 3488-2008 "Test Methods for Microstructure of Cemented Carbide": used for grain size and microstructure analysis.

related to mechanical properties of cemented carbide :

ISO 28079:2009 "Test method for fracture toughness of carbide palm-shaped specimens": Test K_{Ic} ($8-16\ \text{MPa}\cdot\text{m}^{1/2}$).

ISO 6507-1:2018 "Vickers hardness test for metallic materials": Applicable to cemented carbide hardness testing.

ISO 3327:2009 Test method for compressive strength of cemented carbide: Test compressive strength (4000-6000 MPa).

ISO 3738-1:2010 Test methods for wear of cemented carbides: Based on abrasive wear testing (similar to ASTM G65).

American standards related to mechanical properties of cemented carbide:

ASTM E399-20 Test Method for Fracture Toughness of Metallic Materials: Test K_{Ic} , applicable to cemented carbide.

ASTM E647-15 "Fatigue Crack Growth Rate Test Method": Test crack growth rate (da/dN).

ASTM E23-18 "Notched Specimen Impact Test Method": Charpy and Izod test impact energy.

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ASTM G65-16 Dry Sand/Rubber Wheel Wear Test Method: Tests the wear resistance of cemented carbide (wear rate $<0.1 \text{ mm}^3 / \text{N} \cdot \text{m}$).

European standards related to mechanical properties of cemented carbide:

EN ISO 6507-1:2018 "Vickers hardness test": consistent with ISO 6507-1.

EN 843-1:2006 Test method for fracture toughness of advanced ceramics: Applicable to K_{Ic} test of cemented carbide.

EN 1071-3:2005 "Test methods for wear of ceramic materials": Applicable to the wear resistance test of cemented carbide.

EN ISO 6892-1:2019 "Tensile testing of metallic materials": can be used for strength testing of cemented carbide.

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Schedule:

The balance between hardness and toughness of cemented carbide: main performance parameters

performance	Parameter range	Application Scenario	Remark
Hardness (HV)	15002500±30	Aviation tools, mining drill bits, wear-resistant molds	High hardness (HV>2000±30) can easily lead to a decrease in toughness and requires balance and optimization.
Toughness (K _{1c})	820 MPa·m ^{1/2} ± 0.5	Aviation tools, mining drill bits, wear-resistant molds	High toughness (K _{1c} >15 MPa·m ^{1/2} ± 0.5) is often accompanied by a decrease in hardness, which affects wear resistance.
Compressive strength	>4000 MPa±100 MPa	High load conditions	It is closely related to grain size and Co content.
Cutting life	>20 hours ±1 hour	Aviation tools (high speed cutting > 1000 m/min)	Fine-grained WCCo (0.5μm±0.01μm, Co 10%±1%), hardness HV 1800±30, extended service life.
Drilling distance	>1500 m±100 m	Mining drill bits	Co 8%±1% optimizes toughness and improves drilling efficiency.
Number of squeezes	>10 ⁶ times ±10 ⁵ times	Wear-resistant mold	Grain refinement (0.5μm±0.01μm) improves durability.

Factors affecting the grain size effect on the balance between hardness and toughness of cemented carbide

factor	Parameter range	Impact on performance	Optimization suggestions
Initial powder particle size	0.51μm±0.01μm	Particle size <1μm increases hardness (HV>1800±30); >2μm hardness <1500±30.	Use 0.51μm±0.01μm powder to ensure uniform refinement.
Ball milling time	40 hours ± 1 hour (400 rpm ± 10 rpm)	After 40 hours, the size is reduced to 0.5μm±0.01μm, and the hardness increases by 30%±5%; after <20 hours, the size is >1μm, and the performance decreases.	Ball milling was performed for 40 h ± 1 h, and the rotation speed was controlled at 400 rpm ± 10 rpm.
Sintering temperature	1450°C±10°C	At 1450°C, the grain size is <0.7μm±0.01μm; at >1500°C, the grain size is >2μm, and the hardness decreases by 10%±2%.	Control 1450°C±10°C to avoid grain growth.
Additives (VC)	0.3%±0.01%	0.3% inhibits grain growth and increases hardness by 5%±1%; >0.5% forms brittle phase, K _{1c} <8 MPa·m ^{1/2} ± 0.5.	Add VC 0.3%±0.01% and control the grain size to <0.5μm±0.01μm.
Co content	10%±1%	10% has balanced hardness (HV 1800±30) and toughness (K _{1c} >12 MPa·m ^{1/2} ± 0.5); <6% has insufficient toughness.	Set Co 10%±1% to ensure balanced performance.
Sintering atmosphere	Vacuum degree <10 ⁻³ Pa ± 10 ⁻⁴ Pa	Vacuum avoids oxidation (O ₂ < 0.1 ppm±0.01 ppm) and reduces grain boundary defects (<0.1%±0.02%).	Use vacuum or high-purity Ar atmosphere (purity>99.99%±0.01%).

Influencing factors of binder phase content optimization for hardness and toughness balance of cemented carbide

factor	Parameter range	Impact on performance	Optimization suggestions
Co ratio	8%10%±1%	± 30) and toughness (K _{1c} 12 MPa·m ^{1/2} ± 0.5); <6% K _{1c} <10 MPa·m ^{1/2} ± 0.5 .	Select Co 8%10%±1% to ensure

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factor	Parameter range	Impact on performance	Optimization suggestions
			balanced performance.
Sintering temperature	1450°C±10°C	1450°C ensures uniform distribution of Co (deviation <1%±0.2%); >1500°C forms a Co pool (>10µm±1µm).	Control 1450°C±10°C, Co distribution deviation <1%±0.2%.
WC particle size	0.51µm±0.01µm	0.51µm enhances interfacial bonding; >2µm K _{1c} decreases by 5%±1%.	Select WC 0.51µm±0.01µm.
Additives (VC)	0.3%±0.01%	0.3% controls Co diffusion (rate <10 ⁻¹⁰ cm ² /s ± 10 ⁻¹¹ cm ² /s); >0.5% forms a brittle phase (>1%±0.2%).	Adding VC 0.3%±0.01% can inhibit Co diffusion.
Molding pressure	250 MPa±5 MPa	250 MPa increases density (>99.5%±0.1%); <200 MPa porosity>2%±0.5%.	Use cold isostatic pressing at 250 MPa±5 MPa.
Sintering time	2 hours ± 0.1 hours	Controlled Co wetting for 2 hours (contact angle <5°±1°); Co segregation rate >0.5%±0.1% for >3 hours.	Sintering was performed for 2 hours ± 0.1 hours to ensure the uniformity of Co.

Main performance parameters of cemented carbide fatigue resistance and impact resistance

performance	Parameter range	Application Scenario	Remark
Crack growth rate (da/ dN)	<10 ⁻⁶ mm/cycle±10 ⁻⁷ mm/cycle	Mining drill bits, aviation cutting tools, wear-resistant molds	Low crack growth rate (e.g. 10 ⁻⁷ mm/cycle ± 10 ⁻⁸ mm/cycle) extends fatigue life (> 10 ⁵ times ± 10 ⁴ times).
Impact energy	1050 J ± 1 J	Mining drill bits, aviation cutting tools, wear-resistant molds	Charpy impact energy 20 J ± 1 J meets high impact requirements (e.g. > 10 ³ Hz ± 100 Hz).
Fatigue life	>10 ⁵ times ±10 ⁴ times	Mining drill bits, wear-resistant molds	Grain refinement (0.5µm±0.01µm) and Co optimization (10%±1%) significantly improve fatigue resistance.
Impact life	Drilling>1500 m±100 m, extrusion>10 ⁶ times±10 ⁵ times	Mining drill bits, wear-resistant molds	High K _{1c} (12 MPa·m ^{1/2} ± 0.5) ensures reliability against shocks.

Factors affecting crack growth on fatigue resistance of cemented carbide

factor	Parameter range	Impact on performance	Optimization suggestions
Grain size	0.51µm±0.01µm	0.51µm da/ dN <10 ⁻⁷ mm/cycle±10 ⁻⁸ mm/cycle; >2µm da/ dN >10 ⁻⁶ mm/cycle±10 ⁻⁷ mm/cycle.	Select WC 0.51µm±0.01µm.
Co content	10%±1%	10% K _{1c} >12 MPa·m ^{1/2} ± 0.5, low da/ dN ; <6% da/ dN increase by 30%±5%.	Set Co 10%±1%.
Stress ratio (R)	0.1±0.01	R=0.1 da/ dN <10 ⁻⁷ mm/cycle±10 ⁻⁸ mm/cycle; R>0.5 da/ dN increased by 50%±5%.	Control R=0.1±0.01.
Additives (VC)	0.3%±0.01%	0.3% increases grain boundary strength (>200 MPa±20 MPa); >0.5% brittle phase >1%±0.2%.	Add VC 0.3%±0.01%.
Surface roughness	Ra<0.05µm±0.01µm	Ra<0.05µm, crack initiation time>10 ⁴ times ±10 ³ times; >0.1µm, life span is reduced by 20%±5%.	Polish to Ra<0.05µm±0.01µm.
Microscopic	Porosity <0.5%±0.1%	Porosity <0.5% da/ dN <10 ⁻⁷ mm/cycle±10 ⁻⁸ mm/cycle; >1% da/ dN increase	The porosity is controlled to

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factor	Parameter range	Impact on performance	Optimization suggestions
defects		by 40%±5%.	<0.5%±0.1% and detected by CT scanning.

Factors affecting impact toughness of cemented carbide impact resistance

factor	Parameter range	Impact on performance	Optimization suggestions
Co content	10%±1%	10% impact energy>20 J±1 J; <6% impact energy<10 J±1 J.	Select Co 10%±1%.
Grain size	0.51μm±0.01μm	0.51μm $K_{1c} > 12 \text{ MPa} \cdot \text{m}^{1/2} \pm 0.5$; >2μm, the impact energy decreases by 20%±5%.	Select WC 0.51μm±0.01μm.
Additives (VC)	0.3%±0.01%	0.3% impact energy increases by 10%±2%; >0.5% brittle phase >1%±0.2%.	Add VC 0.3%±0.01%.
Notch depth	2 mm±0.01 mm	2 mm standard test; >3 mm impact energy reduction 30%±5%.	Control the notch depth to 2 mm ± 0.01 mm.
Sintered density	>99.5%±0.1%	>99.5% impact energy>20 J±1 J; <99% porosity>2%±0.5%.	Ensure sintering density>99.5%±0.1%.
Test temperature	40°C±1°C	At 40°C, the impact energy is >15 J±1 J; at <60°C, the impact energy decreases by 20%±5%.	Low temperature testing verifies performance (40°C ± 1°C).

Main performance parameters of cemented carbide failure mechanism

performance	Parameter range	Failure scenarios	Remark
Wear rate	<0.06 mm ³ / N · m ± 0.01 mm ³ / N · m	Mining drill bits, aviation cutting tools, wear-resistant molds	High wear rates (>0.06 mm ³ / N · m ± 0.01 mm ³ / N · m) leading to reduced tool life (e.g. tool <10 hours ±1 hour).
Crack length	<0.1 mm±0.01 mm	Aviation tools, mining drill bits	Micro cracks (>0.1 mm ± 0.01 mm) cause spalling and reduce reliability.
Fracture rate	<0.1%±0.02%	Aviation tools, wear-resistant molds	High K_{1c} (12 MPa·m ^{1/2} ± 0.5) reduces the risk of fracture .
Peeling rate	<0.1%±0.02%	Mining drill bits, wear-resistant molds	Interfacial energy >1 J/m ² ± 0.1 J/m ² reduces spalling.

Factors affecting wear failure of cemented carbide

factor	Parameter range	Impact on performance	Optimization suggestions
hardness	HV 1800±30	HV 1800±30: wear rate <0.06 mm ³ / N · m ± 0.01 mm ³ / N · m ; <1500±30: increase by 30%±5%.	Ensure hardness HV 1800±30.
Grain size	0.51μm±0.01μm	0.51μm: low wear rate; >2μm: increase by 20%±5%.	Select WC 0.51μm±0.01μm.
Co content	10%±1%	10% less adhesive wear; >12% wear rate increases by 15%±3%.	Set Co 10%±1%.
Surface roughness	Ra<0.05μm±0.01μm	Ra<0.05μm, the wear rate is low; >0.1μm, it increases by 25%±5%.	Polish to Ra<0.05μm±0.01μm.
Operating temperature	<800°C±10°C	>800°C Adhesive wear increases by 50%±5%.	Use coolant to control the temperature <600°C±10°C.
Abrasive	<50μm±5μm	<50μm: wear rate<0.06 mm ³ / N · m ± 0.01 mm ³ / N · m ; >100μm:	Control abrasive particle size

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factor	Parameter range	Impact on performance	Optimization suggestions
particle size		wear rate increases by 40%±5%.	<50μm±5μm.

Factors affecting fracture and spalling of cemented carbide

factor	Parameter range	Impact on performance	Optimization suggestions
Toughness (K _{1c})	>12 MPa·m ^{1/2} ± 0.5	K _{1c} >12 MPa·m ^{1/2} ± 0.5, the fracture rate is <0.1%±0.02%; <10 MPa·m ^{1/2} ± 0.5, the fracture rate increases by 50%±5%.	Ensure K _{1c} >12 MPa·m ^{1/2} ± 0.5.
Grain size	0.51μm±0.01μm	The crack growth rate of 0.51μm is slow; the fracture rate of >2μm increases by 30%±5%.	Select WC 0.51μm±0.01μm.
Co content	10%±1%	10% less peeling; <6% peeling rate increases by 20%±5%.	Set Co 10%±1%.
Surface defects	Crack<0.1 mm±0.01 mm	For cracks > 0.1 mm, the fracture rate increases by 50% ± 5%.	CT scanning was used to detect cracks and polish the surface.
Stress concentration factor (K _t)	<2±0.1	K _t >3 , the peeling rate increases by 40%±5%.	Rounded corners (radius > 0.5 mm ± 0.01 mm), K _t < 2 ± 0.1.
Interface Energy	>1 J/m ² ± 0.1 J/m ²	>1 J/m ² , the spalling rate decreases by 20%±5%; <0.5 J/m ² , the spalling rate increases by 30%±5%.	Optimized interfacial energy >1 J/m ² ± 0.1 J/m ² .

Main performance parameters of cemented carbide performance improvement

performance	Parameter range	Application Scenario	Remark
Hardness (HV)	18002500±30	Aviation tools, mining drill bits, wear-resistant molds	Ultrafine grains (<0.2μm±0.01μm) and surface strengthening (such as laser cladding) can reach >3000±50.
Toughness (K _{1c})	1015 MPa·m ^{1/2} ± 0.5	Mining drill bits, wear-resistant molds	Additives (VC, TaC) and Co optimization (10%±1%) increase K _{1c} to above 12 MPa·m ^{1/2} ± 0.5 .
Fatigue life	>10 ⁵ times ±10 ⁴ times	Wear-resistant molds, mining drill bits	PIII (10 ¹⁸ cm ⁻² ± 10 ¹⁶ cm ⁻²) extends lifespan to >10 ⁶ times ±10 ⁵ times.
Wear rate	<0.06 ± 0.01 mm ³ / N·m	Aviation tools, mining drill bits	Ion implantation and laser cladding can be reduced to <0.04 mm ³ / N·m ± 0.01 mm ³ / N·m .

Grain refinement and additives influencing factors for improving cemented carbide performance

factor	Parameter range	Impact on performance	Optimization suggestions
Grain size	<0.5μm±0.01μm	<0.5μm hardness>2000±30; >1μm hardness<1800±30.	Select WC<0.5μm±0.01μm and ball mill for 40 hours±1 hour.
Additives (VC/ TaC)	0.3%±0.01%	0.3% hardness increases by 5%±1%, K _{1c} increases by 10%±2%; >0.5% brittle phase>1%±0.2%.	Add VC/ TaC 0.3%±0.01%.
Ball milling time	40 hours ± 1 hour	After 40 hours, the grain size is <0.5μm±0.01μm; after <20 hours, the grain size is >1μm±0.01μm.	Ball mill for 40 h ± 1 h (500 rpm ± 10 rpm).
Sintering temperature	1450°C±10°C	At 1450°C, the grains are stable; at >1500°C, the grains are >1μm±0.01μm.	Controlled at 1450°C±10°C, pressure <10 ⁻³ Pa ± 10 ⁻⁴ Pa .

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factor	Parameter range	Impact on performance	Optimization suggestions
Co content	10%±1%	10% K _{1c} >12 MPa·m ^{1/2} ± 0.5; <6% K _{1c} <10 MPa·m ^{1/2} ± 0.5.	Set Co 10%±1%.
ZrC addition	0.2%±0.01%	0.2% hardness>2500±50;>0.5% K _{1c} decreases by 10%±2%.	Add ZrC 0.2%±0.01% for ultrafine grain WC.

Factors affecting surface strengthening of cemented carbide performance improvement

factor	Parameter range	Impact on performance	Optimization suggestions
Carburizing temperature	900°C±10°C	A WC layer (1050μm±1μm, HV>2500±50) is formed at 900°C; the crack rate is>1%±0.2% at >1000°C.	Controlled temperature: 900°C±10°C, CH ₄ flow rate: 10 L/min±0.1 L/min.
Ion dose	10 ¹⁷ cm ⁻² ± 10 ¹⁶ cm ⁻²	10 ¹⁷ cm ⁻² hardness >2200±30;>10 ¹⁸ cm ⁻² damage >1%±0.2%.	Using N ⁺ , dose 10 ¹⁷ cm ⁻² ± 10 ¹⁶ cm ⁻² , energy 100 keV±1 keV.
Grain size	0.51μm±0.01μm	0.51μm has the best strengthening effect; >2μm hardness increase is <10%±2%.	Select WC 0.51μm±0.01μm.
Co content	10%±1%	10% strengthening layer is stable; <6% crack rate increases by 20%±5%.	Set Co 10%±1%.
Surface roughness	Ra<0.05μm±0.01μm	Ra<0.05μm has low wear rate;>0.1μm increases by 15%±3%.	Polish to Ra<0.05μm±0.01μm.
Laser power	2 kW±0.1 kW	2 kW cladding layer is uniform (thickness 50100μm±1μm); >3 kW crack rate increases by 10%±2%.	The laser power was controlled at 2 kW±0.1 kW and the scanning speed was controlled at 10 mm/s±0.1 mm/s.

appendix:

What is the Hall-Petch relationship ?

The Hall-Petch relationship is a classic theoretical model that describes the relationship between the mechanical properties of materials (mainly strength and hardness) and grain size. It is widely used in metals, alloys and ceramic materials (such as cemented carbide WC-Co). This relationship shows that as the grain size decreases, the strength and hardness of the material will increase significantly. The core mechanism is the hindering effect of grain boundaries on dislocation movement. The Hall-Petch relationship was first proposed by EO Hall and NJ Petch in 1951 and 1953 respectively, and is mainly used to study the mechanical behavior of polycrystalline materials.

Basic concepts and formulas

The Hall-Petch relationship can be expressed by the following mathematical formula:

$$\sigma_y = \sigma_0 + k d^{-1/2}$$

或对于硬度:

$$HV = HV_0 + k' d^{-1/2}$$

其中:

- σ_y : 材料的屈服强度 (单位: MPa) 。
- HV : 材料的硬度 (例如维氏硬度, 单位: HV) 。
- σ_0 或 HV_0 : 单晶材料的屈服强度或硬度 (晶粒尺寸趋于无穷大时的极限值), 反映晶粒内部的固有阻力。
- k 或 k' : Hall-Petch常数, 与材料类型和晶界特性相关 (单位: $\text{MPa} \cdot \text{m}^{1/2}$ 或 $\text{HV} \cdot \text{m}^{1/2}$) 。
- d : 平均晶粒尺寸 (单位: m, 通常为 μm 量级) 。
- $d^{-1/2}$: 晶粒尺寸的倒数平方根, 表示晶界密度的增加。

直观解释: 晶粒尺寸越小 (d 越小), $d^{-1/2}$ 越大, 晶界密度越高, 位错运动受阻越明显, 因此材料的强度和硬度 (σ_y 或 HV) 越高。

Microscopic mechanism

The physical basis of the Hall-Petch relationship is the hindering effect of grain boundaries on dislocation motion. The mechanical properties of polycrystalline materials are mainly affected by the following mechanisms:

Grain boundaries hinder dislocation motion :

In polycrystalline materials, grain boundaries between grains are natural obstacles to dislocation movement. Dislocations are carriers of plastic deformation of materials. When dislocations move to grain boundaries, they cannot easily cross grain boundaries due to the orientation difference of grain boundaries (grain boundary deflection angle is usually 20° - 40°) and grain boundary energy ($>1.5 \text{ J/m}^2$) .

Dislocations accumulate at grain boundaries, forming dislocation pile-ups, which lead to local stress

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concentrations. Crossing grain boundaries requires higher applied stresses, which manifests as an increase in yield strength.

Increased grain boundary density :

As the grain size decreases (e.g., from 2 μm to 0.5 μm), the density of grain boundaries increases significantly (from $\sim 10^{12} \text{ m}^{-2}$ to $> 10^{13} \text{ m}^{-2}$). The higher the density of grain boundaries, the more obstacles there are to dislocation movement per unit volume, and the strength and hardness of the material increase accordingly.

decreases from 2 μm to 0.5 μm , the grain boundary density increases by about 4 times, and the hardness increase can reach 25%-30% (such as from HV 1200 to HV 1600).

Orowan strengthening mechanism :

Grain boundaries enhance material properties by pinning dislocations (similar to the Orowan strengthening mechanism).

晶界通过钉扎位错（类似Orowan强化机制）增强材料性能。位错绕过晶界的剪应力 (τ) 与晶界间距 (λ) 相关: $\tau \sim Gb/\lambda$, 其中 G 为剪切模量, b 为伯氏矢量, λ 与晶粒尺寸 d 成正比 ($\lambda \sim d$)。晶粒尺寸越小, λ 越小, 剪应力越高, 材料越强硬。

Grain Boundary Migration and Stability :

The thermodynamic stability of grain boundaries has an important influence on the Hall-Petch relationship. The grain boundary migration rate (usually $< 10^{-10} \text{ m/s}$) is controlled by the sintering temperature (1400-1500°C) and additives (such as VC 0.2%-0.5%), and the migration barrier is 80-120 kJ/mol. Stable grain boundaries (low migration rate) help to maintain a fine grain structure and thus maintain high strength.

Scope of application of Hall-Petch relationship

The Hall-Petch relationship works very well within a certain range of grain sizes, but fails in extreme cases:

Applicable scope (large grain size, $> 0.2 \mu\text{m}$) :

For most cemented carbides (such as WC-Co), the Hall-Petch relationship holds true when the grain size is in the range of 0.2 μm to 10 μm . For example, when the grain size of WC-10Co decreases from 2 μm to 0.5 μm , the hardness increases from HV 1200 to HV 1600, an increase of about 25%-30%, and the yield strength increases by about 20%-25% (from 3500 MPa to 4500 MPa).

At this time, the main strengthening mechanism is the grain boundary hindering the dislocation movement.

Failure range (grain size is too small, $< 0.2 \mu\text{m}$) :

When the grain size is reduced to the nanoscale ($< 0.2 \mu\text{m}$, such as $< 100 \text{ nm}$), the Hall-Petch relationship may fail and the "reverse Hall-Petch effect" may occur. At this time, grain boundary sliding becomes the main deformation mechanism, resulting in a decrease in strength and hardness. Reason: The proportion of grain boundaries is too high ($> 50\%$), the interface energy dominates the

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performance ($>1.5 \text{ J/m}^2$), the grain boundary sliding and diffusion (such as Coble creep) are intensified, and the toughness decreases (K_{IC} drops from $12 \text{ MPa}\cdot\text{m}^{1/2}$ to $<8 \text{ MPa}\cdot\text{m}^{1/2}$).

For example, when the WC grain size is reduced from $0.5 \mu\text{m}$ to $0.1 \mu\text{m}$, the hardness may drop from HV 1600 to HV 1400, and the toughness decreases significantly ($K_{IC} < 8 \text{ MPa}\cdot\text{m}^{1/2}$).

High temperature conditions :

At high temperatures ($>800^\circ\text{C}$), the grain boundary migration rate increases ($>10^{-9} \text{ m/s}$), and the grains may grow abnormally ($>2 \mu\text{m}$), resulting in a weakening of the Hall-Petch effect. For example, at 1000°C , the grain size of WC-10Co may grow from $0.5 \mu\text{m}$ to $2 \mu\text{m}$, and the hardness decreases by 10%-15% (from HV 1600 to HV 1400).

Factors Affecting the Hall-Petch Relationship

The performance of the Hall-Petch relationship is affected by the following factors:

Grain size (d) :

Grain size is the core variable of the Hall-Petch relationship. The smaller the grain, the higher the grain boundary density and the more obvious the strengthening effect. For example, when the WC grain size is reduced from $1 \mu\text{m}$ to $0.5 \mu\text{m}$, the hardness increases by about 15%-20%.

However, grains that are too small ($<0.2 \mu\text{m}$) will lead to the reverse Hall-Petch effect, and additives (such as VC 0.2%-0.5%) are needed to inhibit grain boundary sliding.

Material type and grain boundary characteristics :

Hall-Petch常数 k 与材料类型和晶界特性密切相关。对于硬质合金WC-Co, k 值通常在 $0.5\text{--}1.0 \text{ MPa}\cdot\text{m}^{1/2}$ 之间, 受Co含量和晶界强度影响。

Co含量高(如15%)时, 晶界润湿性增强(接触角 $<15^\circ$), 晶界强度降低($<100 \text{ MPa}$), k 值减小, 强化效果减弱; Co含量低(如6%)时, 晶界强度高($>150 \text{ MPa}$), k 值增大。

3. Additives :

Adding grain inhibitors (such as VC 0.2%-0.5%, Cr_3C_2 0.1%-0.3%) can reduce the grain size and enhance the Hall-Petch effect. For example, adding 0.4% VC can reduce the WC grain size from $1 \mu\text{m}$ to $0.5 \mu\text{m}$ and increase the hardness by 5%-10% (from HV 1500 to HV 1600).

However, excessive additives ($>0.8\%$) may form brittle phases (such as VC_x phase, ratio $>0.5\%$) and reduce toughness ($K_{IC} < 8 \text{ MPa}\cdot\text{m}^{1/2}$).

Sintering process :

Sintering temperature ($1400\text{--}1500^\circ\text{C}$) and vacuum ($<10^{-2} \text{ Pa}$) affect grain size and grain boundary stability. Too high a temperature ($>1550^\circ\text{C}$) will cause grain growth ($>2 \mu\text{m}$) and a 10%-15% drop in hardness.

For example, when WC-10Co is sintered at 1450°C , the grain size remains at $0.5 \mu\text{m}$ and the hardness reaches HV 1600; when sintered at 1600°C , the grain size grows to $2 \mu\text{m}$ and the hardness drops to HV 1400.

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Co content :

The Co content affects the grain boundary wettability and plastic deformation ability. When the Co content is low (such as 6%), the grain boundary strengthening effect is significant and the hardness is high ($HV > 1600$); when the Co content is high (such as 15%), the grain boundary softens and the hardness decreases ($HV < 1200$).

For example, WC-6Co (grain size $0.5 \mu m$) has a hardness of HV 1700, while WC-15Co (same grain size) has a hardness of only HV 1200.

Microscopic defects :

Porosity ($> 1\%$) and microcracks (length $> 0.05 mm$) weaken the grain boundary strengthening effect and reduce hardness and strength. For example, an increase in porosity from 0.5% to 2% reduces the hardness by about 5% (from HV 1600 to HV 1520).

Application of cemented carbide

In cemented carbides (such as WC-Co), the Hall-Petch relationship is widely used to control grain size to optimize properties:

Grain refinement increases hardness :

The grain size was reduced from $2 \mu m$ to $0.5 \mu m$ by high-energy ball milling (300-500 rpm, 20-40 hours), addition of grain inhibitors (such as VC 0.2%-0.5%) and optimized sintering process ($1400-1500^{\circ}C$, vacuum $< 10^{-2} Pa$).

Result: The hardness increased from HV 1200 to HV 1600, and the yield strength increased from 3500 MPa to 4500 MPa, meeting the requirements of high-speed cutting ($> 800 m/min$).

Balance of hardness and toughness :

Too small grains ($< 0.2 \mu m$) will lead to reduced toughness ($K_{IC} < 8 MPa \cdot m^{1/2}$), which is not suitable for high impact scenarios (such as mining drill bits). Therefore, the grain size needs to be controlled in the range of $0.5-1 \mu m$ to achieve a balance between hardness (HV 1600) and toughness ($K_{IC} 12-14 MPa \cdot m^{1/2}$).

For example, WC-10Co (grain size $0.5 \mu m$) has a hardness of HV 1600 and a K_{IC} of $12 MPa \cdot m^{1/2}$, making it suitable for aviation tools.

Engineering application optimization :

μm through Hall-Petch relationship, hardness reaches HV 1700, and cutting life > 15 hours.

Mining drill bit: grain size $0.8 \mu m$, hardness HV 1500, $K_{IC} 13 MPa \cdot m^{1/2}$, drilling distance $> 1200 m$.

Wear-resistant mold: grain size $0.5 \mu m$, hardness HV 1600, extrusion times $> 10^6$ times.

Limitations and Challenges

Although the Hall-Petch relationship is widely used in cemented carbides, it also has the following limitations and challenges:

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Reverse Hall-Petch effect :

the grain size is too small ($<0.2\ \mu\text{m}$), the deformation is dominated by grain boundary sliding and diffusion, and the strength and hardness decrease. For example, if the WC grain size is reduced from $0.5\ \mu\text{m}$ to $0.1\ \mu\text{m}$, the hardness may drop from HV 1600 to HV 1400.

Challenges of grain boundary stability :

sintering time (>4 hours) will cause grain growth ($>2\ \mu\text{m}$), reducing the Hall-Petch effect. VC or Cr_3C_2 needs to be added to inhibit grain growth.

Risks of reduced resilience :

Although grain refinement increases hardness, it may lead to a decrease in toughness ($K_{\text{IC}} < 10\ \text{MPa}\cdot\text{m}^{1/2}$), and the performance needs to be balanced by optimizing the Co content (8%-12%) and grain size ($0.5\text{-}1\ \mu\text{m}$).

The impact of micro defects :

Porosity ($>1\%$) and microcracks (length $>0.05\ \text{mm}$) can weaken the grain boundary strengthening effect. For example, the hardness of highly porous WC-10Co (2% porosity) is only HV 1520, which is much lower than expected (HV 1600).

Development Trend

With the development of materials science and intelligent manufacturing, the application of Hall-Petch relationship in cemented carbide is deepening:

Nanocrystalline and ultrafine crystal technology :

Develop ultrafine-grained ($<0.5\ \mu\text{m}$) and nanocrystalline ($<100\ \text{nm}$) cemented carbides with a hardness of up to HV 2000, but the problem of grain boundary sliding needs to be solved (such as adding TaC 0.2%-0.5% to improve grain boundary strength).

Gradient structure design :

The Hall-Petch relationship is used to design a gradient structure cemented carbide with fine surface grains ($0.2\text{-}0.5\ \mu\text{m}$, hardness HV 1700) and slightly larger internal grains ($1\text{-}2\ \mu\text{m}$, $K_{\text{IC}} > 14\ \text{MPa}\cdot\text{m}^{1/2}$), achieving synergistic optimization of hardness and toughness.

AI-Assisted Optimization :

AI is used to predict the effect of grain size on performance (prediction accuracy $> 90\%$) and optimize ball milling and sintering parameters. For example, machine learning can be used to predict the optimal grain size ($0.5\ \mu\text{m}$) with a hardness deviation of $<2\%$.

Improved high temperature performance :

Develop high temperature stable grain boundary inhibitors (such as ZrC 0.1%-0.3%) to maintain grain size ($<1\ \mu\text{m}$) at $>800^\circ\text{C}$ and maintain the Hall-Petch effect.

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In summary, the Hall-Petch relationship reveals the influence of grain size on the mechanical properties of cemented carbide and is the theoretical basis for grain refinement and performance optimization. By rationally regulating grain size and grain boundary characteristics, hardness and strength can be significantly improved, but attention should be paid to the balance between toughness and high-temperature stability. With the introduction of new technologies and intelligent manufacturing, the Hall-Petch relationship will play a greater role in the field of cemented carbide.

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appendix

What is Gradient Structure Cemented Carbide ?

Gradient structure cemented carbide refers to a type of cemented carbide (WC-Co) that is designed and regulated so that its microstructure or composition (such as grain size, bonding phase content or additive distribution) presents a gradient change along a specific direction (such as from the surface to the inside) inside the material. This structure is designed to combine the performance advantages of different regions, such as high surface hardness and high internal toughness, to meet the comprehensive performance requirements of harsh working conditions (such as aviation tools and mining drills). Compared with traditional cemented carbide, gradient structure cemented carbide has significant advantages in performance optimization, but it also poses new challenges to traditional grades and production methods, and at the same time puts higher requirements on intelligent production design control AI Agent.

Basic concepts and principles of gradient structure cemented carbide

Cemented carbide is usually composed of a hard phase (such as WC, which has high hardness but high brittleness) and a bonding phase (such as Co, which has good toughness but low hardness). Traditional cemented carbide (such as YG6, YG8 and other grades) has a uniform microstructure, and the Co content and grain size are basically consistent throughout the material, making it difficult to meet the requirements of high hardness and high toughness at the same time. For example, YG6 (Co 6%) has high hardness (HV 1600-1700), but low toughness ($K_{IC} \approx 8-10 \text{ MPa} \cdot \text{m}^{1/2}$); YG15 (Co 15%) has good toughness ($K_{IC} \approx 14-16 \text{ MPa} \cdot \text{m}^{1/2}$), but reduced hardness (HV 1200-1300).

Gradient structure cemented carbide achieves synergistic optimization of functions by introducing performance gradients in different areas of the material:

surface

The Co content is low (such as 4%-6%), the grain size is fine (such as $0.2-0.5 \mu\text{m}$), the hardness is high (HV 1600-1800), the wear resistance is strong, and it is suitable for withstanding high friction and wear.

Middle Layer

The Co content and grain size gradually transition (such as Co 8%-10%, grain $0.5-1 \mu\text{m}$), thickness $0.5-2 \text{ mm}$, and relieve interface stress concentration ($<80 \text{ MPa}$).

internal

The Co content is relatively high (e.g. 12%-15%), the grain size is slightly larger (e.g. $1-2 \mu\text{m}$), the toughness is excellent ($K_{IC} \approx 14-16 \text{ MPa} \cdot \text{m}^{1/2}$), the impact resistance is strong, and it can absorb crack energy and prevent fracture.

This gradient distribution is achieved by regulating Co diffusion, grain growth and sintering processes. The mechanical properties are based on composite material theory (such as the Voigt model, $E \sim V_{WC} \cdot E_{WC} + V_{Co} \cdot E_{Co}$) and the Hall-Petch relationship ($\sigma \sim d^{-1/2}$), so that the material has different hardness, strength and toughness at different depths. The gradient structure can also be further optimized by controlling the interface energy ($<1.5 \text{ J/m}^2$) and grain boundary

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dynamics (migration rate $<10^{-10}$ m/s).

Gradient structure design method

The design of gradient structure cemented carbide mainly focuses on the following aspects:

Co content gradient:

The Co content on the surface is low (4%-6%), the middle layer has 8%-10%, and gradually increases to 12%-15% inside.

Principle: When the Co content is low, the WC volume fraction is high ($>90\%$) and the hardness is improved; when the Co content is high, the plastic deformation ability is enhanced (strain rate $\sim 10^{-3} \text{ s}^{-1}$) and the toughness is improved.

Implementation method: Through layered powder ratio (Co powder ratio increases from outside to inside) or control the Co diffusion rate during sintering ($<10^{-9} \text{ cm}^2/\text{s}$). For example, three layers of powder are stacked: surface layer Co 4%, middle layer Co 8%, inner layer Co 12%, and a gradient is formed through liquid phase sintering.

Grain size gradient:

The surface grains are fine ($0.2\text{-}0.5 \mu\text{m}$), the middle layer is $0.5\text{-}1 \mu\text{m}$, and the internal grains are slightly larger ($1\text{-}2 \mu\text{m}$).

Principle: Small grains increase hardness and strength through the Hall-Petch effect ($\text{HV} \sim d^{1/2}$); larger grains reduce grain boundary sliding (grain boundary area $<10^{13} \text{ m}^{-2}$) and improve toughness.

Implementation method: Add grain inhibitors on the surface (such as VC 0.2%-0.5%, Cr_3C_2 0.1%-0.3%), reduce inhibitors in the middle layer and inside; or control the grain growth rate through layered sintering (surface $<10^{-10}$ m/s, slightly higher inside).

Additive distribution gradient:

Add more VC or Cr_3C_2 (0.2%-0.5%) on the surface to inhibit grain growth and enhance hardness; add a small amount of TaC (0.1%-0.3%) in the middle layer to increase grain boundary strength ($>150 \text{ MPa}$); add TaC (0.2%-0.5%) inside to further enhance toughness.

Implementation method: Layered additive ratio, combined with sintering process control. For example, add 0.4% VC to the surface layer, 0.2% TaC to the middle layer, and 0.3% TaC to the inner layer.

Functional Gradient:

A wear-resistant coating (such as CrN or TiN, thickness $2\text{-}4 \mu\text{m}$, hardness HV 3000-3500) is introduced on the surface, the middle layer optimizes fatigue resistance (crack growth rate $\text{da}/\text{dN} <10^{-7} \text{ mm/cycle}$), and the internal part optimizes impact resistance (impact energy $>18 \text{ J}$).

Implementation method: Combination of surface modification (such as carburizing, ion implantation) and internal microstructure optimization.

Multiphase Gradient:

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Introducing a multiphase structure, such as adding a small amount of TiC (hardness > 2000 HV, 5%-10%) on the surface to enhance wear resistance, the middle layer is a WC-Co transition layer, and the WC-Co structure is maintained inside to ensure toughness.

Implementation method: Add TiC powder in layers and form a multiphase gradient through sintering.

Diversification of gradient directions:

In addition to radial gradients from the surface to the inside, lateral gradients (such as high hardness of the tool cutting edge and high toughness of the clamping part) or multi-directional gradients (suitable for complex geometric parts) can also be designed.

Implementation method: Use 3D printing technology (such as selective laser melting SLM) to accurately control the composition and structure of each area.

Preparation technology of gradient structure cemented carbide

The preparation of gradient structure cemented carbide needs to be achieved through the following processes:

Powder Proportioning and Forming

The green body was prepared by layered powder method, with WC-Co mixed powders with different Co contents, grain sizes or additive ratios used on the surface, middle and inside. For example, surface layer (Co 4%, WC 0.5 μm), middle layer (Co 8%, WC 1 μm), inner layer (Co 12%, WC 1.5 μm).

Cold isostatic pressing (CIP, pressure 200-300 MPa) is used to ensure the density (>99%) and uniformity (porosity <0.5%) of the green body.

Precision requirements: powder ratio deviation <0.1%, layer thickness deviation <0.02 mm, interlayer bonding strength >50 MPa.

Sintering process:

Liquid phase sintering (1400-1500°C, 1-3 hours, vacuum degree <10⁻² Pa), the Co diffusion rate (<10⁻⁹ cm²/s) is controlled by temperature gradient and time to form a gradient distribution.

Sintering temperature gradient

The surface temperature is slightly lower (1400°C), which inhibits grain growth; the middle layer is 1420°C, and the inner part is 1450-1500°C, which promotes Co diffusion and moderate grain growth.

Sintering atmosphere: vacuum or Ar atmosphere (purity>99.99%), avoid oxidation (O₂ content <0.5 ppm), reduce grain boundary defects (<0.2%).

Cooling rate: controlled at 3-5°C/min to avoid thermal stress (<100 MPa); if >10°C/min, the microcrack rate is >0.5%.

Heat treatment and surface modification

Annealing (550-650°C, 1-2 hours) reduces the internal stress of the Co phase (<50 MPa) and increases K_{1c} by about 5%.

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Surface carburizing (850-950°C, CH₄ atmosphere, carbon layer thickness 10-30 μm) or ion implantation (N⁺, dose 10¹⁶-10¹⁷ cm⁻², energy 80-120 keV) to form a high hardness layer (HV 1800-2000).

Laser cladding (power 1.5-2.5 kW, thickness 50-100 μm) forms an ultra-high hardness layer (HV>2500).

Plasma enhanced ion implantation (PIII, dose 10¹⁷-10¹⁸ cm⁻²) improves deep wear resistance (depth > 0.5 μm).

Online monitoring and control

using a laser particle size analyzer (deviation <0.02 μm), and the grain boundary stress (<100 MPa) was evaluated using X-ray diffraction (XRD, peak width deviation <0.2°).

The sintering process was monitored in real time using a temperature sensor (accuracy ±2°C), a pressure sensor (accuracy ±10⁻³ Pa) and an online microscope (resolution <0.1 μm) to ensure the consistency of the gradient structure (deviation <0.5%).

Acoustic emission technology (frequency range 20 kHz-500 kHz) was used to detect microcracks (length > 0.05 mm) during the sintering process.

Performance characteristics and advantages of gradient structure cemented carbide

Gradient structure cemented carbide exhibits the following characteristics through the coordinated optimization of performance:

Balance of hardness and toughness

High surface hardness (HV 1600-1800) and excellent internal toughness (K_{IC} 14-16 MPa·m^{1/2}), overcoming the contradiction between hardness and toughness of traditional cemented carbide.

For example, gradient WC-10Co with 4% Co on the surface and 0.5 μm grain has a hardness of HV 1700, 12% Co inside and K_{IC} 14 MPa·m^{1/2}, and its comprehensive performance is better than that of traditional YG8 (Co 8%, HV 1500, K_{IC} 12 MPa·m^{1/2}).

Synergistic improvement of wear resistance and impact resistance

High surface hardness and low Co content reduce wear rate (<0.08 mm³ / N·m); high Co content inside increases impact energy (18-20 J).

Suitable for high friction and impact scenarios, such as mining drill bits with a lifespan of >1500 m in hard rock drilling, which is 50% higher than traditional YG6.

Excellent anti-fatigue performance

improves fatigue life (>10⁵ times) by reducing surface crack initiation (crack length <0.05 mm) and internal crack growth rate (da/dN <10⁻⁷ mm/cycle).

For example, the life of gradient WC-10Co under cyclic loading (stress ratio R=0.1, frequency 5-15 Hz) is 20%-30% higher than that of traditional YG10 (Co 10%).

Thermal shock resistance

The gradient structure reduces thermal stress concentration (<80 MPa) and improves thermal shock

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resistance by 15%-20% under high temperature ($>800^{\circ}\text{C}$) conditions, making it suitable for aviation tools (cutting temperature $>800^{\circ}\text{C}$).

Corrosion resistance

The low Co content on the surface reduces corrosion sensitivity (dissolution rate $<10^{-10} \text{ g/cm}^2 \cdot \text{s}$) and improves corrosion resistance by 10%-15% in acidic environments ($\text{pH} < 5$), making it suitable for marine engineering applications.

Adapt to harsh working conditions

Under high temperature ($>800^{\circ}\text{C}$), high impact ($>500 \text{ Hz}$), high stress ($>80 \text{ MPa}$) and corrosive environment (NaCl concentration 3.5%), the gradient structure can effectively extend the service life. For example, the life of deep-sea drill bits is increased by 50%, and the life of high-speed rail brake pad molds is increased by 60%.

Challenges of Gradient Structure Cemented Carbide to Traditional Cemented Carbide Grades

The introduction of gradient structure cemented carbide has brought many challenges to traditional cemented carbide grades (such as YG series and YT series):

Performance limitations revealed

Traditional grades have a uniform structure and are difficult to meet the needs of complex working conditions. For example, YG6 (Co 6%) has a high hardness ($\text{HV } 1600$), but is easy to break in high impact scenarios (such as mining) ($K_{\text{IC}} < 10 \text{ MPa} \cdot \text{m}^{1/2}$); YG15 (Co 15%) has good toughness ($K_{\text{IC}} > 14\text{-}16 \text{ MPa} \cdot \text{m}^{1/2}$), but has insufficient hardness ($\text{HV} < 1300$) and poor wear resistance.

Gradient structure cemented carbide exceeds the performance limit of traditional grades by combining high surface hardness ($\text{HV } 1700$) and high internal toughness ($K_{\text{IC}} > 14 \text{ MPa} \cdot \text{m}^{1/2}$). For example, the cutting life (>15 hours) of gradient WC-10Co in aviation tools is 25% higher than that of YG8.

Competition in application areas

Traditional grades still have advantages in specific areas (such as low impact and low friction scenarios), such as YG3 (Co 3%) for low-load cutting. However, gradient structure cemented carbide is more competitive in high-load and multi-functional scenarios (such as aviation and deep sea). For example, the drilling distance of gradient WC-10Co in deep-sea drill bits ($>1500 \text{ m}$) far exceeds that of YG8 ($<1000 \text{ m}$).

Traditional brands need to upgrade their formulas or introduce gradient structures to maintain their market competitiveness, otherwise they may be gradually eliminated in the high-end market.

Complexity of production process

The production process of traditional grades is simple (uniform powder ratio + single sintering) and

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low cost (about 50-60 yuan/kg). Gradient structure cemented carbide requires layered powder mixing, gradient sintering and online monitoring, which is complex and increases the cost by 15%-20% (about 60-70 yuan/kg).

Traditional production equipment (such as ordinary sintering furnaces) can hardly meet the precision requirements of gradient structures (such as Co distribution deviation <0.5%) and needs to be upgraded to high-precision equipment (such as gradient sintering furnaces with temperature gradient control accuracy of $\pm 2^{\circ}\text{C}/\text{cm}$).

The challenge of standardization

Traditional grades have mature standards (such as ISO K10, K20, P10), clear performance parameters, and are easy to mass produce and apply. Gradient structure cemented carbide has performance that changes with depth and is difficult to define with a single standard, so a new performance evaluation system needs to be established (such as layered testing of hardness and toughness).

$K_{10} < 14 \text{ MPa}\cdot\text{m}^{1/2}$) of gradient WC-10Co cannot be directly matched to the traditional ISO standard, which may cause confusion for users when selecting materials.

Market acceptance and promotion

Traditional grades have a long history and high market recognition, and users are familiar with their performance and application range. As an emerging technology, gradient structure cemented carbide needs to gain trust through long-term application verification (such as aviation tool life testing).

In the early stages of promotion, users' concerns about cost and performance stability need to be addressed, for example, by demonstrating its advantages through demonstration projects (such as increasing the life of mining drill bits by 50%).

Adaptability of supply chain and material selection

The supply chain of traditional grades is mature, the raw materials (such as WC powder, Co powder) are of uniform specifications, and the procurement cost is low. Gradient structure cemented carbide requires powders of various specifications (such as WC with different particle sizes and different Co contents), which increases the complexity and cost of the supply chain.

Users need to re-evaluate their material selection strategies. The traditional simple selection method of grades (such as based on hardness or Co content) is no longer applicable, and layered performance testing and simulation analysis need to be introduced.

Requirements for Intelligent Production Design Control AI Agent

The production of gradient structure cemented carbide has put forward higher requirements for intelligent manufacturing. The intelligent production design control AI Agent needs to have the following capabilities to achieve efficient, accurate and stable production:

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Microstructure prediction and optimization

Ability requirements: AI Agent needs to predict the impact of Co content, grain size and additive ratio on performance through machine learning (ML) and deep learning (DL) algorithms (such as support vector machine SVM, deep neural network DNN) (prediction accuracy > 90%).

Specific functions

Based on historical data and physical models (such as Hall-Petch relationship, Voigt model), the optimal Co content gradient is predicted (for example, 4% on the surface, 8% in the middle layer, and 12% in the interior, with a deviation of <0.2%).

Optimized grain size distribution (0.5 μm on the surface, 1 μm in the middle layer, 1.5 μm in the interior, with a deviation of <0.02 μm) ensures a synergistic improvement in hardness (HV 1700) and toughness (K_{IC} 14 $\text{MPa}\cdot\text{m}^{1/2}$).

Recommended additive ratio (such as VC 0.4%, TaC 0.2%, Cr₃C₂ 0.1%, ratio deviation <0.05%) to improve performance consistency (deviation <0.5%).

Simulate the layered performance of gradient structures (such as surface wear resistance and internal impact resistance) to optimize design solutions.

Real-time process parameter monitoring and control

Ability requirements: AI Agent needs to combine Industrial Internet of Things (IIoT) technology to monitor and control production parameters in real time (deviation <1%) through embedded sensors and edge computing.

Specific functions

Monitor powder ratio (Co content accuracy $\pm 0.05\%$), grain size (accuracy $\pm 0.005 \mu\text{m}$) and additive distribution (deviation <0.1%).

Real-time adjustment of sintering parameters: temperature (1400-1500°C, accuracy $\pm 2^\circ\text{C}$), vacuum degree ($<10^{-2}$ Pa, accuracy $\pm 10^{-3}$ Pa), Co diffusion rate ($<10^{-9}$ cm^2/s , deviation <5%).

Control the cooling rate (3-5°C/min, deviation <0.2°C/min) to avoid thermal stress (<100 MPa) and micro cracks (rate <0.5%).

Monitor interlayer bond strength (>50 MPa) and avoid delamination defects (crack length >0.05 mm).

Failure Prediction and Quality Control

Ability requirements: AI Agent needs to predict potential failure risks in the production process (such as Co segregation, abnormal grain growth) through neural networks (such as RNN, LSTM) and intervene in advance (prediction advance time > 10^3 times).

Specific functions

μm) caused by the Co distribution deviation (>1%) was predicted, and the sintering time was adjusted in advance (1-3 hours, deviation <0.1 hour).

abnormal grain growth (>2 μm) was identified, and the growth was inhibited by adjusting the VC addition amount (0.2%-0.5%).

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Combining acoustic emission sensors (frequency accuracy ± 2 kHz) and CT scanning (accuracy ± 0.02 mm), microcracks (length > 0.05 mm) can be detected in real time, reducing failure rate ($< 0.1\%$).

Detect interlaminar stress concentration ($K_t > 1.5$) and avoid interface peeling (depth > 5 μm).

Process optimization and intelligent decision making

Ability requirements: AI Agent needs to optimize production process parameters through genetic algorithms (GA) or reinforcement learning (RL) to improve production efficiency (increase by 15%-20%) and performance consistency (deviation $< 2\%$).

Specific functions

The layered powder ratio was optimized (surface Co 4%, middle layer 8%, inner layer 12%, deviation $< 0.1\%$) to ensure the uniformity of the gradient structure.

The sintering temperature gradient was adjusted (1400°C for the surface, 1420°C for the middle layer, and 1450°C for the inner layer, with a deviation of $< \pm 2^\circ\text{C}/\text{cm}$) to control Co diffusion and grain growth.

Optimize the additive ratio ($\text{VC}:\text{TaC}:\text{Cr}_3\text{C}_2 = 2:1:0.5$, deviation $< 0.05\%$) to improve hardness and toughness ($\text{HV } 1700$, $K_{IC} 14 \text{ MPa} \cdot \text{m}^{1/2}$).

Through process data analysis, the ball milling time (20-40 hours, accurate to ± 0.5 hours) and rotation speed (300-500 rpm, accuracy ± 5 rpm) are automatically adjusted to improve production efficiency.

Data integration and multi-source collaboration

Ability requirements: AI Agent needs to integrate multi-source data (powder characteristics, sintering parameters, performance test results) and achieve multi-device collaboration through 5G network and cloud platform (delay < 10 ms).

Specific functions

Integrate powder particle size data (laser particle size analysis, deviation < 0.02 μm), sintering temperature data (sensor accuracy $\pm 2^\circ\text{C}$) and performance test data (hardness deviation $< 2\%$).

data analysis to optimize production parameters (e.g., Co diffusion rate is controlled at $< 10^{-9} \text{ cm}^2/\text{s}$).

Coordinated control of ball mill (speed accuracy ± 5 rpm), sintering furnace (temperature deviation $< \pm 2^\circ\text{C}$) and detection equipment (XRD peak width deviation $< 0.2^\circ$).

Achieve cross-line collaboration, such as synchronously adjusting the temperature gradients of multiple sintering furnaces (deviation $< \pm 1^\circ\text{C}/\text{cm}$).

Intelligent maintenance and adaptive adjustment

Ability requirements: AI Agent needs to predict the failure time of equipment and products through crack growth data (error < 5 hours) and optimize maintenance strategies (reducing downtime by 30%-35%).

Specific functions

Predict Co segregation (deviation $> 1\%$) caused by sintering furnace temperature deviation ($> \pm 10^\circ\text{C}$) and adjust parameters in advance.

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Combining acoustic emission and CT data, the fatigue failure of gradient structure cemented carbide in service is predicted ($>10^4$ times in advance) and the maintenance cycle is optimized.

Adaptively adjust production parameters, such as adjusting VC addition (increase 0.1%-0.2%) based on real-time hardness data (HV deviation $> 2\%$).

Predict equipment wear (e.g. ball mill bearing life, error <10 hours), replace parts in advance and reduce downtime.

User demand customization and feedback learning

Ability requirements: AI Agent needs to customize gradient structure design according to user needs (such as high hardness of aviation cutting tools and high toughness of mining drill bits), and continuously optimize through feedback learning (performance improvement of 5%-10%).

Specific functions

According to the requirements of aviation tools (hardness $HV > 1700$), a gradient structure with surface Co 4% and grain size of $0.5 \mu m$ was designed.

According to the requirements of mining drill bits ($K_{1c} > 14 MPa \cdot m^{1/2}$), the internal Co 12% and grain size $1.5 \mu m$ structure is designed.

Collect application feedback data (such as tool life, drill wear rate) and optimize Co content and grain distribution through reinforcement learning (error $< 0.1\%$).

According to the user's working conditions (such as high temperature $> 800^\circ C$), a surface coating solution (such as CrN, thickness $3 \mu m$) is recommended.

Environmental adaptation and energy consumption optimization

Ability requirements: AI Agent needs to optimize process parameters and reduce energy consumption (by 10%-15%) based on the production environment (such as temperature and humidity) and energy consumption requirements.

Specific functions

Monitor ambient humidity ($< 50\%$) to avoid corrosive effects ($< 5\%$ increase in wear rate).

Optimize the energy consumption of the sintering furnace (temperature control accuracy $\pm 2^\circ C$) and reduce ineffective heating time (saving 5%-10%).

Adaptively adjust the equipment operating power according to the production batch size (for example, reduce the ball mill speed to 300 rpm for small batch production).

Influencing factors of gradient structure cemented carbide

The performance and production of gradient structures are affected by the following factors:

Co content distribution

The Co content gradient needs to be controlled within a reasonable range (4%-6% on the surface, 8%-10% in the middle layer, and 12%-15% in the interior). If the surface Co is $< 4\%$, $K_{1c} < 8 MPa \cdot m^{1/2}$; if the internal Co is $> 15\%$, the hardness is < 1200 .

Grain size distribution

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The surface grain size is $<0.5\ \mu\text{m}$, the middle layer is $0.5\text{--}1\ \mu\text{m}$, and the internal layer is $1\text{--}2\ \mu\text{m}$. If the surface grain size is $>1\ \mu\text{m}$, the hardness is <1500 . If the internal grain size is $<0.5\ \mu\text{m}$, $K_{1c} < 10\ \text{MPa}\cdot\text{m}^{1/2}$.

Sintering process

Temperature deviation ($>\pm 10^\circ\text{C}$) or insufficient vacuum ($>10^{-2}\ \text{Pa}$) can lead to uneven Co distribution (deviation $>1\%$), the formation of Co pools (size $>5\ \mu\text{m}$), and a 10%-15% decrease in toughness.

additive

Excessive VC ($>0.8\%$) will lead to a brittle phase ratio of $>0.5\%$, reducing K_{1c} ; insufficient TaC ($<0.1\%$) will result in low grain boundary strength ($<100\ \text{MPa}$).

Equipment accuracy

Insufficient ball mill speed accuracy ($<\pm 5\ \text{rpm}$) and sintering furnace temperature accuracy ($<\pm 2^\circ\text{C}$) can lead to grain size deviation ($>0.02\ \mu\text{m}$) and uneven Co distribution (deviation $>0.5\%$).

Environmental factors

The humidity of the production environment ($>80\%$) may cause powder oxidation (O_2 content $>0.5\ \text{ppm}$) and affect the stability of the gradient structure (hardness deviation $>2\%$).

Engineering Application of Gradient Structure Cemented Carbide

Gradient structure cemented carbide performs well in a variety of demanding scenarios:

Aviation tools

Surface Co 4%, hardness HV 1700, internal Co 12%, $K_{1c} 14\ \text{MPa}\cdot\text{m}^{1/2}$, in high-speed cutting ($>800\ \text{m/min}$), life >15 hours, an increase of 25%, better than traditional YG8.

Mining drill bits

The surface grain size is $0.5\ \mu\text{m}$, the internal Co content is 12%, and the service life in hard rock drilling is $>1500\ \text{m}$, an increase of 50%, surpassing traditional YG6.

Deep sea drill

Gradient structure (surface Co 4%, middle layer 8%, inner layer 12%), in deep sea impact ($>500\ \text{Hz}$, pressure $>80\ \text{MPa}$), K_{1c} reaches $14\ \text{MPa}\cdot\text{m}^{1/2}$, drilling distance $>1500\ \text{m}$.

High-speed rail brake pad mold

Surface hardness HV 1700, internal $K_{1c} 14\ \text{MPa}\cdot\text{m}^{1/2}$, life span $>4 \times 10^5$ times in high temperature friction ($>600^\circ\text{C}$), an increase of 60%.

New energy electrolyzer

Surface addition of TiC 5%, hardness HV 1800, internal Co 12%, $K_{1c} 13\ \text{MPa}\cdot\text{m}^{1/2}$, in electrochemical shock ($>10^3$ times), life $>10^3$ hours, an increase of 40%.

Wind turbine blade mold

Surface Co 4%, CrN coating $3\ \mu\text{m}$, internal Co 12%, in low temperature impact (-60°C , strain rate $>10^3\ \text{s}^{-1}$), impact energy $>12\ \text{J}$, life $>10^6$ times, an increase of 40%.

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Advantages and disadvantages of gradient structure cemented carbide

Advantages:

Hardness and toughness are optimized synergistically, with excellent overall performance, surpassing traditional grades.

Adapt to a variety of harsh working conditions and extend service life.

Smart production improves consistency and efficiency.

Disadvantages:

The preparation process is complex and requires high-precision equipment (such as a gradient sintering furnace with a temperature gradient control accuracy of $\pm 2^{\circ}\text{C}/\text{cm}$).

Higher cost (15%-20% higher than traditional grades).

The AI Agent has high requirements for intelligence and needs a large amount of data support.

Development trend of gradient structure cemented carbide

With the in-depth development of intelligent manufacturing, the production and application of gradient structure cemented carbide will become more intelligent:

Deep integration of AI+IIoT

Through reinforcement learning and big data analysis, AI Agent optimizes gradient structure design (Co distribution error $< 0.1\%$) and improves performance consistency (deviation $< 0.5\%$).

IIoT uses 5G networks and cloud platforms to achieve multi-device collaboration (delay $< 10\text{ ms}$) and improve production efficiency ($> 20\%$).

3D Printing Technology Application

3D printing technology (such as selective laser melting SLM) is used to achieve more complex gradient structures (such as multi-layer, multi-phase gradient), with grain size deviation $< 0.01\text{ }\mu\text{m}$ and Co distribution deviation $< 0.1\%$.

New gradient structure

Develop multiphase gradients (such as WC- TiC -Co composite gradients) and multifunctional gradients (such as surface corrosion resistance and internal high toughness) to meet the diverse needs of aviation, deep sea, new energy and other fields.

Standardization and promotion

Establish performance evaluation standards for gradient structure cemented carbide (such as layered hardness and toughness testing) to promote its widespread application in the global market.

Green Manufacturing

Use AI to optimize energy consumption (reduce by 10%-15%) and develop recyclable gradient structure cemented carbide (such as Co content stratified recycling) to achieve sustainable development.

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In summary, the gradient structure cemented carbide achieves a synergistic improvement in hardness, toughness and wear resistance through the gradient design of the microstructure, challenging the performance limit of traditional cemented carbide grades. The introduction of intelligent production design control AI Agent further improves production accuracy and efficiency, promotes the development of cemented carbide towards high performance and intelligence, and provides more efficient and reliable solutions for aviation, mining, new energy and other fields.

CTIA GROUP LTD

30 Years of Cemented Carbide Customization Experts

Core Advantages

30 years of experience: We are well versed in cemented carbide production and processing , with mature and stable technology and continuous improvement .

Precision customization: Supports special performance and complex design , and focuses on customer + AI collaborative design .

Quality cost: Optimized molds and processing, excellent cost performance; leading equipment, RMI, ISO 9001 certification.

Serving Customers

The products cover cutting, tooling, aviation, energy, electronics and other fields, and have served more than 100,000 customers.

Service Commitment

1+ billion visits, 1+ million web pages, 100,000+ customers, and 0 complaints in 30 years!

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appendix:

Various concepts and functions of cemented carbide carburizing

Carburizing technology for cemented carbide (WC-Co) is a process that introduces carbon elements into the material surface through high-temperature thermochemical treatment to improve surface properties. The application of carburizing in cemented carbide mainly focuses on improving hardness, wear resistance, corrosion resistance and fatigue resistance while maintaining internal toughness. This article will discuss the nature of carburizing, process form, mechanism of action, key influencing factors and actual application effects, aiming to reveal its unique value in optimizing cemented carbide performance.

The essence of carburizing: surface diffusion and reaction of carbon

The core of carburizing lies in the diffusion and reaction of carbon atoms at high temperatures. Cemented carbide is composed of a hard phase of tungsten carbide (WC) and a bonding phase of cobalt (Co). The Co phase has a high carbon solubility (about 0.2-0.3 wt % at 900°C), which becomes the main channel for carbon diffusion. During the carburizing process, carbon atoms are decomposed from external carbon sources (such as CH₄, CO or solid carbon powder), diffuse to the surface through the Co phase lattice, and then react with WC to form a denser carbide structure or thicken existing WC particles. This diffusion-reaction mechanism forms a carbon-rich area on the surface, usually manifested as a WC-rich layer with a thickness of 10-50 μm.

The carburizing temperature is usually in the range of 850-950°C, which is lower than the sintering temperature of cemented carbide (1400-1500°C) to avoid grain coarsening or matrix performance degradation. The carbon diffusion rate ($\sim 10^{-11}$ cm²/s) determines the thickness and quality of the carburized layer and needs to be precisely controlled by temperature, carbon potential and time.

Carburizing process: from traditional to modern

The carburizing process takes many forms depending on the carbon source and energy supply method. Each form has different application scenarios and effects in cemented carbide:

Gas carburizing:

Using hydrocarbons (such as CH₄) or carbon monoxide (CO) as the carbon source, it is carried out in a controlled atmosphere at 850-950°C. CH₄ decomposes into active carbon atoms (C) and H₂, and the carbon atoms diffuse to the surface: $\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$. Gas carburizing is suitable for mass production, with uniform carburized layer thickness (10-30 μm) and hardness up to HV 2000-2200, but the carbon potential (0.8-1.2 wt %) needs to be precisely controlled to avoid over-carburization or decarburization.

Solid carburizing:

The carbide sample is buried in carbon powder (such as graphite), heated at 900-950°C, and carbon diffuses through direct contact. The solid carburizing equipment is simple and suitable for small-scale experiments, but the uniformity of the carburized layer is poor (thickness deviation ± 5 μm) and the efficiency is low.

Plasma carburizing:

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In a plasma environment at 700-900°C, an electric field is used to activate a carbon source (such as CH_4) to generate highly active carbon ions. Plasma accelerates carbon diffusion (rate increased to $\sim 10^{-10} \text{cm}^2 / \text{s}$), forming a 20-40 μm carburized layer at a lower temperature with a hardness of HV 2200-2500, while reducing energy consumption (approximately 20 %-30%).

Laser-assisted carburizing:

Use laser (power 1-2 kW) to locally heat the surface, combined with a carbon source (such as carbon powder coating) to achieve carburizing. Laser carburizing is fast (<1 hour), the thickness of the carburized layer is controllable (5-20 μm), and it is suitable for complex geometric parts, but microcracks may be introduced in the heat-affected zone.

These process forms have their own focus. Gas carburizing is suitable for industrial production, plasma carburizing emphasizes high efficiency and low consumption, and laser carburizing is suitable for high-precision local strengthening.

The role of carburizing: multi-dimensional performance improvement

The influence of carburizing on the performance of cemented carbide is multifaceted, mainly reflected in the following key effects:

Improved hardness and wear resistance:

The WC-rich layer (thickness 10-30 μm) formed by carburization significantly increases the surface hardness (HV 2000-2500), which is much higher than the matrix (HV 1500-1800). The high-hardness carbide layer enhances the ability to resist abrasive wear and sliding wear, and the wear rate can be reduced to $<0.08 \text{mm}^3 / \text{N} \cdot \text{m}$. For example, in cutting tool applications, carburized cemented carbide tools can withstand higher cutting speeds ($>1000 \text{m/min}$) and increase their life by 20%-30%.

Improved corrosion resistance:

The WC-rich layer reduces the exposure of the Co phase and improves the surface stability in acidic ($\text{pH} < 5$) or oxidizing environments ($>600^\circ\text{C}$). After carburizing, a thin layer of Co_3C or Co_2C may form on the surface of the Co phase, further inhibiting the corrosion reaction and extending the service life of the material under corrosive conditions (such as deep-sea valves).

Improved fatigue resistance:

The residual compressive stress ($>400 \text{MPa}$) introduced by carburizing is generated through volume expansion, which effectively inhibits the initiation and propagation of surface cracks, and the fatigue life can be increased to $>10^5$ times. Especially in high-cycle loading scenarios (such as aviation tools), the carburized layer significantly improves reliability.

Microstructure optimization:

During carburizing, carbon atoms are embedded in the WC lattice or thickened carbide particles, the grain boundary bonding strength is enhanced ($>150 \text{MPa}$), and the tendency of intergranular fracture is reduced. SEM analysis shows that the fracture surface after carburizing is mainly composed of small dimples ($<1 \mu\text{m}$), indicating that the proportion of plastic fracture has increased.

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Improved thermal stability: The

carburized layer improves the surface's resistance to high temperature softening and can maintain high hardness (>1800 HV) at 600-800°C, making it suitable for high temperature cutting or stamping die applications.

It is worth noting that carburizing does not have a positive effect on all properties. Too thick a carburized layer (>50 μm) may increase surface brittleness and reduce fracture toughness (K_{IC}) by 5%-10%. Process optimization is required to balance hardness and toughness.

Key influencing factors: core control points for performance optimization

The carburizing effect is affected by the combined effects of process parameters, material properties and external conditions. The following are the key factors:

Temperature and time:

The temperature is 850-950°C for the best range, and the thickness of the carburized layer increases linearly with time (2-10 hours) (thickness 10-50 μm). Too high temperature (>1000°C) will cause the Co phase to soften or the grains to coarsen (>2 μm), and the hardness will drop by 15%-20%. Too long a time (>12 hours) may cause internal decarburization and affect the matrix performance.

Carbon potential control:

The carbon potential (carbon content) needs to be maintained at 0.8-1.2 wt %. If it is too low (<0.6 wt %), the carburized layer will be incomplete and the hardness will be insufficient. If it is too high (>1.5 wt %), an over-carbon layer (such as free carbon) will be formed, which will increase brittleness.

Material microstructure:

Co content: Co content of 8%-12% provides the best carbon diffusion channel. Too low (<6%) limits carbon diffusion, and too high (>15%) causes surface softening.

WC grain size: When the grain size is <0.5 μm, the bonding strength of the carburized layer is strong and the hardness increases significantly; when the grain size is >2 μm, the carbon diffusion is uneven and the hardness increases by <10%.

Surface condition:

Initial roughness R_a <0.1 μm ensures tight adhesion of the carburized layer; if >0.2 μm, defects may occur in the carburized layer and the wear rate will increase by 15%-20%.

Post-treatment conditions:

Low-temperature tempering (200-400°C, 1-2 hours) after carburizing can release residual stress (<100 MPa), but if the temperature is too high (>500°C), the hardness of the carburized layer will decrease.

Practical application effects: from laboratory to engineering practice

The application of carburizing technology in the field of cemented carbide is relatively mature, and its actual effect has been verified in many engineering scenarios:

Cutting tools:

WC-10Co tools are carburized (carburized layer 20 μm, hardness HV 2000). In high-speed cutting (>1000 m/min), the service life is increased by 25% and the cutting efficiency is increased by 20%.

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It is suitable for aviation aluminum alloy processing.

Mining drill bit: After carburizing the

WC-8Co drill bit (15 μm carburizing layer), the wear rate is reduced to $<0.08 \text{ mm}^3 / \text{N} \cdot \text{m}$, the drilling distance is extended to $>1500 \text{ m}$, the efficiency is increased by 50%, and the mining cost is significantly reduced.

Stamping die:

WC-12Co die carburizing (carburizing layer 30 μm , hardness >2200), extrusion times $>10^6$ times, increased by 25%, to meet high-frequency stamping needs.

Deep-sea equipment: The service life of

WC-10Co deep-sea valves (25 μm permeation layer) is extended to >4 years in high pressure ($>80 \text{ MPa}$) and corrosive environment ($\text{pH} <5$), an increase of 40%, showing excellent corrosion resistance.

Limitations and improvement directions of carburizing technology

Although carburizing technology has significantly improved the performance of cemented carbide, it still has the following limitations:

Brittleness risk: Too thick a carburized layer ($>50 \mu\text{m}$) may cause surface embrittlement, reducing K_{IC} by 5%-10%, limiting dynamic loading applications.

Process complexity: Carbon potential control is difficult, requiring high-precision equipment (temperature deviation $<\pm 5^\circ\text{C}$), which increases production costs (approximately 15%-20%).

Depth limitation: Carburizing depth is usually $<50 \mu\text{m}$, which cannot meet the requirements of deep strengthening.

Improvements include:

Composite strengthening: Combining carburizing and coating technology (such as TiN coating) to form a gradient structure and improve deep-layer performance.

Intelligent control: Develop an intelligent carburizing system to monitor the carbon potential and carburizing layer thickness in real time through sensors to improve process stability.

Low-cost carbon sources: Explore biochar or waste gas recovery carbon sources to reduce costs and improve sustainability.

Through the surface diffusion and reaction of carbon elements, cemented carbide carburizing technology forms a high-hardness WC-enriched layer, which significantly improves the hardness, wear resistance, corrosion resistance and fatigue resistance. Different process forms (such as gas carburizing and plasma carburizing) provide diverse application methods, and their effects are optimized by regulating temperature, carbon potential and microstructure. Despite the challenges of brittleness and cost, carburizing technology has shown great potential in cutting tools, mining and deep-sea equipment, and is expected to further break through limitations in the future through composite strengthening and intelligent development.

Comparison table of various concepts and functions of cemented carbide carburizing

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project	Unintentional carburization (poor carbon control during production)	Process carburizing (hard alloy performance improvement process)
Definition and Essence	Due to uncontrolled carbon potential or fluctuations in the carbon content of the raw materials during the production process (such as sintering), carbon atoms accidentally diffuse to the surface to form an unexpected carburized layer.	High temperature thermochemical treatment process introduces carbon elements into the surface of cemented carbide to optimize performance by precisely controlling the carbon source, temperature and time.
Process form	- Occurs in production links such as sintering, without specific process control. - Carbon source : excess carbon in the atmosphere (such as CH ₄ decomposition). - Temperature: sintering temperature (1300-1500°C).	- Gas carburizing: CH ₄ or CO, 850-950°C. - Solid carburizing: Carbon powder contact, 900-950°C . - Plasma carburizing: CH ₄ plasma activation, 700-900°C. - Laser-assisted carburizing: Laser heating, power 1-2 kW.
Characteristics of the permeable layer	- Thickness: 5-60 μm , non-uniform. - Hardness: HV 1800-2200, large fluctuations (deviation ±200 HV). - May be accompanied by free carbon or decarburization.	- Thickness: 10-30 μm , uniform. - Hardness: HV 2000-2500, stable (deviation < ±50 HV). - WC-rich layer is dense.
Hardness and wear resistance	- Hardness increased to HV 1800-2200, but uneven distribution. - Wear resistance improved, wear rate <0.1 mm ³ / N · m , but local over-carbonization reduces the effect.	- Hardness increased to HV 2000-2500, uniform. - Wear resistance significantly improved, wear rate <0.08 mm ³ / N · m , suitable for high-load friction scenarios.
Corrosion resistance	- The carburized layer is uneven, local over-carburization forms free carbon, which is easily soluble, the Co phase is more exposed, and the corrosion resistance decreases (such as pH <5 environment).	- The WC-rich layer reduces the exposure of the Co phase, improves corrosion resistance, and is suitable for acidic (pH <5) or high temperature oxidative (>600°C) environments.
Anti-fatigue performance	- Uneven residual stress (locally <200 MPa) may introduce micro cracks and reduce fatigue life (<10 ⁴ times).	- Residual compressive stress >400 MPa, fatigue life increased to >10 ⁵ times, suitable for high cycle loading scenarios.
Microstructure	- The grain boundary bonding strength is uneven (locally <100 MPa), the proportion of intergranular fracture is high (>50%), and the structural stability is poor.	- The grain boundary bonding strength is enhanced (>150 MPa), the fracture is mainly dimples (<1 μm), the plasticity and brittleness are balanced, and the structure is stable.
Thermal stability	- Local over-carbonization leads to uneven thermal stability and a significant drop in hardness (<1500 HV) at high temperatures (>600°C).	- The carburized layer maintains a hardness of >1800 HV at 600-800°C, suitable for high temperature cutting or stamping die applications.
Fracture toughness (K _{1c})	- Too thick a carburized layer (>50 μm) or too much carburized layer leads to increased brittleness and a decrease in K _{1c} by 10%-20% (<10 MPa·m ^{1/2}).	- Moderately carburized layers (<30 μm) are carbon saturated by the Co phase , increasing K _{1c} by 5%-10% (10-14 MPa·m ^{1/2}).
Temperature	- Temperature: 1300-1500°C (sintering temperature),	- Temperature: 850-950°C, time 2-10 hours, thickness of the

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project	Unintentional carburization (poor carbon control during production)	Process carburizing (hard alloy performance improvement process)
and time	time is uncontrollable and may be too long (>10 hours), resulting in over-carburization or decarburization.	diffusion layer 10-50 μm , precise control.
Carbon Potential	- Uncontrolled carbon potential (>1.5 wt % or <0.6 wt %), resulting in incomplete or over-carburized cases.	- Carbon potential 0.8-1.2 wt %, precisely regulated by mass flow controller to ensure uniform carburization layer.
Co content	- Fluctuations in Co content affect carbon diffusion, <6% results in restricted diffusion, >15% results in softening.	- 8%-12% provides the best diffusion channel, with a balance between toughness and hardness.
WC grain size	- When the grain size is >2 μm , carbon diffusion is uneven and performance fluctuates greatly.	- When the grain size is <0.5 μm , the bonding strength of the carburized layer is strong and the hardness increases significantly (>10%).
Surface state	- The surface condition is not controlled, Ra fluctuates greatly, which may affect the adhesion of the carburized layer.	- Polishing to Ra <0.1 μm ensures tight adhesion of the carburized layer and reduces the wear rate by 15%-20%.
Controllability and repeatability	- Uncontrollable, large performance differences between batches (deviation > 20%).	- Controllable, batch deviation <5%, stable performance.
Positive Case	- Not applicable, usually considered a manufacturing defect.	μm infiltration layer , HV 2000), life expectancy increased by 25%. - Mining drill bits: WC-8Co (15 μm infiltration layer), drilling distance > 1500 m, increased by 50%. - Stamping dies: WC-12Co (30 μm infiltration layer), extrusion times > 10^6 times, increased by 25%. - Deep-sea equipment: WC-10Co (25 μm infiltration layer), life expectancy > 4 years, increased by 40%.
Negative Cases	- A batch of WC-10Co drill bits had a high carbon potential (>1.5 wt %), a carburized layer of 60 μm , a $K_{IC} < 10 \text{ MPa} \cdot \text{m}^{1/2}$, and premature fracture (lifespan <10*times) .	- Not applicable, process carburizing can avoid this problem.
Improvement direction	- Optimize the carbon content of the raw materials (deviation < 0.1 wt %), improve atmosphere control and reduce unintentional carburization.	-The intelligent carburizing system monitors the carbon potential in real time and combines coating technology to form a gradient structure to improve deep-layer performance.

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appendix:

Carburizing and decarburizing of cemented carbide

Cemented carbide (mainly composed of tungsten carbide WC and bonding phases such as Co and Ni, with a WC content of 85-94 wt % and a bonding phase of 6-15 wt %) is widely used in mining picks, tools, seals and molds due to its high hardness (1400-2200 HV), high strength (1.82-8 GPa) and excellent wear resistance. Carburizing and decarburization are two key processes involving carbon content regulation in the preparation and use of cemented carbide, which directly affect the microstructure, performance and life of the material. Carburizing introduces carbon into the surface of cemented carbide to enhance the surface hardness, wear resistance and corrosion resistance; decarburization causes performance degradation due to carbon loss and is often avoided.

This article combines national standards (such as GB/T 18376-2014, GB/T 5169-2013) with industry practices, elaborates on the carburizing and decarburization mechanism, process, influence and control measures of cemented carbide, and moderately recommends CTIA GROUP LTD's capabilities in carburizing process optimization and decarburization control.

1. Carburizing of cemented carbide

1.1 Definition and mechanism of carburizing

Carburizing is the process of diffusing carbon atoms into the material through a high-temperature atmosphere (such as C_2H_2 , CH_4) or a solid carbon source (such as graphite) on the surface or near-surface area of cemented carbide to form a high-carbon phase (such as WC or η phase), thereby improving the surface hardness (increase by 10-20%), wear resistance (wear loss reduced by 20-30%) and corrosion resistance (corrosion rate <0.01 mm/y).

Carburizing mechanism:

Carbon diffusion: Carbon atoms diffuse through WC grain boundaries and Co phase at high temperatures (1000-1200°C) with a diffusion coefficient $D \approx 10^{-12} - 10^{-11} \text{ m}^2/\text{s}$.

Carburized phase formation:

Low carbon area: Carbon reacts with W to form WC (hardness 2000-2200 HV), enhancing wear resistance.

High carbon region: Excess carbon may form η phase (such as Co_3W_3C , hardness >2500 HV, high brittleness).

Surface modification: The carburized layer (0.1-1 mm) forms a gradient structure with hardness varying from the surface (2000-2200 HV) to the core (1400-1600 HV).

Carburizing purpose:

Improves surface hardness (up to 10-15%) and wear resistance (wear rate $<0.05 \text{ mm}^3/\text{h}$, ASTM G65).

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Enhanced corrosion resistance ($\text{H}_2\text{SO}_4/\text{H}_2\text{S} < 0.01 \text{ mm/y}$, NACE MR0175).

Forming gradient performance, balancing surface wear resistance and core toughness ($\text{KIC } 1215 \text{ MPa} \cdot \text{m}^{1/2}$).

1.2 Carburizing process

Vapor Carburizing:

Introduce carbon source gas (such as C_2H_2 , CH_4) into a vacuum furnace or atmosphere furnace .

Equipment: Vacuum sintering furnace ($10^{-2} \sim 10^{-3} \text{ Pa}$, molybdenum heating elements).

parameter:

Temperature: $1000 \sim 1200^\circ\text{C}$ (WC grains are stable and Co phase does not liquefy).

Gas: C_2H_2 (purity $> 99.9\%$), flow rate 510 L/min , pressure $10^{-2} \sim 10^{-3} \text{ Pa}$.

Time: 13 hours (carburized layer $0.1 \sim 0.5 \text{ mm}$).

Atmosphere: H_2 (510 L/min , to prevent oxidation), $\text{O}_2 < 5 \text{ ppm}$.

result:

Carburized layer thickness: $0.2 \sim 0.5 \text{ mm}$, hardness $2000 \sim 2200 \text{ HV}$.

Carbon content: surface gain $0.51 \text{ wt } \%$, grain size $0.52 \mu\text{m}$.

Porosity: $< 0.01\%$ (GB/T 51692013).

Application: Mining picks (surface wear resistance increased by 20%), cutting tools (cutting life increased by 30%).

Solid phase carburizing:

Method: Place the cemented carbide in graphite powder or carbon black and heat it at high temperature.

Equipment: High temperature furnace (Ar protection, 10^{-2} Pa) .

parameter:

Temperature: $1100 \sim 1300^\circ\text{C}$.

Carbon source: graphite powder ($D_{50} 15 \mu\text{m}$, purity $> 99.9\%$), filling rate $80 \sim 90\%$.

Time: 24 hours (carburized layer 0.51 mm).

Atmosphere: Ar (flow rate 5 L/min , $\text{O}_2 < 10 \text{ ppm}$).

result:

Carburized layer thickness: 0.51 mm , hardness $1900 \sim 2100 \text{ HV}$.

Carbon content: Surface increase $0.81.5 \text{ wt } \%$, η phase may appear.

Adhesion: $> 80 \text{ N}$ (scratch test).

Applications: Moulds (wear resistance increased by 20%), seals (corrosion resistance increased by 15%).

Plasma carburizing:

Method: Plasma discharge enhances the activity of carbon atoms and accelerates their diffusion.

Equipment: Plasma carburizing furnace (glow discharge, $10^{-1} \sim 10^0 \text{ Pa}$).

parameter:

Temperature: $800 \sim 1000^\circ\text{C}$ (low temperature, protecting the substrate).

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Gas: CH₄ (50%) + H₂ (50%), flow rate 1020 sccm .

Voltage: 500800 V, current density 12 mA/ cm² .

Time: 12 hours (carburized layer 0.10.3 mm).

result:

Carburized layer thickness: 0.10.3 mm, hardness 21002300 HV.

Carbon content: surface increase of 0.30.8 wt %, grain stability.

Porosity: <0.001% (high density).

Applications: precision tools (cutting accuracy increased by 10%), deep-sea seals (H₂S resistance <0.005 mm/y).

1.3 Effect of carburization

Carburizing advantages:

Improved hardness: Surface hardness increased by 1015% (20002200 HV), wear resistance increased by 2030% (wear loss <0.05 mm³ / h).

Enhanced corrosion resistance: The carburized layer is dense and the corrosion rate of H₂SO₄/H₂S is <0.01 mm/y.

Extended life: The life of the pick increases by 3050% (10001500 hours), and the cutting life of the tool increases by 2030%.

Disadvantages of carburizing:

η phase risk: Excess carbon forms Co₃W₃C (hardness > 2500 HV, KIC <8 MPa·m^{1/2}), which increases brittleness and the probability of fracture increases by 1020%.

Difficulty in process control: Carbon content deviation > ±0.2 wt % may lead to uneven performance.

Cost increase: carburizing equipment (501 million yuan/unit) and gas cost (C₂H₂ 1020 yuan/m³) .

1.4 Carburizing Case

Mining pick: WC+8%Co (Ø 20 mm), vapor carburizing (1100°C, C₂H₂ 5 L/min, 2 hours), surface hardness 2100 HV, wear <0.05 mm³ / h, life 1200 hours (600 hours for ordinary pick).

Cutting tool: WC+6%Co (Ø 12 mm), plasma carburizing (900°C, CH₄+H₂, 1.5 hours), carburized layer 0.2 mm, hardness 2200 HV, cutting life of Ti alloy increased by 30%.

Seal: YN10 (WC+10%Ni, Ø 50 mm), solid phase carburizing (1200°C, graphite powder, 3 hours), H₂S corrosion resistance rate <0.005 mm/y, life >1000 connections.

2. Decarburization of cemented carbide

2.1 Definition and mechanism of decarbonization

Decarburization is the process of cemented carbide being sintered at high temperature, heat treated or used, where the carbon content on the surface or in the whole is reduced due to carbon loss (reaction with O₂, H₂ or volatilization), forming a low-carbon phase (such as W₂C, Co phase

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enrichment), thereby reducing hardness (reduced by 1020%), wear resistance and strength.

Decarbonization mechanism:

Carbon oxidation: At high temperatures ($>800^{\circ}\text{C}$), carbon reacts with O_2 to form CO/CO_2 , and WC decomposes into W₂C (hardness 16001800 HV, poor wear resistance).

Reaction: $2\text{WC} + \text{O}_2 \rightarrow \text{W}_2\text{C} + \text{CO}_2$.

Carbon volatilization: During vacuum sintering (10^{-4} Pa, $>1400^{\circ}\text{C}$), carbon is lost in gaseous form (C, CO).

Co phase enrichment: After carbon loss, the proportion of Co phase increases (>20 wt %) and a softening layer (hardness <1000 HV) is formed.

Low carbon phase: W₂C (high brittleness, $\text{KIC} < 8 \text{ MPa} \cdot \text{m}^{1/2}$) or free W (hardness <1200 HV), reduces wear resistance.

What happens:

Sintering: Insufficient dewaxing ($\text{O}_2 > 10$ ppm), high temperature oxidation.

Heat treatment: Improper atmosphere control (excess H_2 , O_2 leakage).

Use: High temperature cutting ($>1000^{\circ}\text{C}$, air exposure) or corrosive environment (H_2S induced carbon loss).

2.2 Decarbonization (unintentional)

condition:

Temperature: $>800^{\circ}\text{C}$ (sintering $1350/1450^{\circ}\text{C}$, heat treatment $1000/1200^{\circ}\text{C}$).

Atmosphere: O_2 (>10 ppm), H_2 (flow rate >20 L/min, to induce C volatilization).

Vacuum degree: $>10^{-2}$ Pa (carbon gas loss).

Time: >1 hour (decarburized layer 0.10.5 mm).

result:

Decarburized layer thickness: 0.11 mm, hardness drops to 10001600 HV.

Carbon content: Surface decreased by 0.52 wt %, W₂C ratio increased by 1030%.

Porosity: increased by 0.010.05% (microcracks).

Performance: Wear resistance decreased by 2050% (wear rate $> 0.1 \text{ mm}^3 / \text{h}$), fracture probability increased by 2030%.

2.3 Impact of decarbonization

Decarbonization Disadvantages:

Hardness reduction: surface hardness decreases by 1020% (10001600 HV), and wear resistance decreases by 2050%.

Reduced strength: W₂C is highly brittle, with a 1015% decrease in flexural strength ($<2 \text{ GPa}$) and a 2030% increase in fracture probability.

Corrosion resistance deterioration: the decarburization layer is loose and the corrosion rate increases by 50100% ($\text{H}_2\text{SO}_4 > 0.05 \text{ mm/y}$).

Shortened life: The life of the pick is reduced by 3050% (<500 hours), and the cutting efficiency of

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the tool is reduced by 20%.

Decarbonization Case:

Failure of pick: WC+10%Co (Ø 20 mm), sintered (1450°C, O₂ 20 ppm), surface decarburization layer 0.3 mm, hardness 1400 HV, wear 0.15 mm³ / h, life 400 hours (normal 800 hours).

Tool wear: WC+6%Co (Ø 12 mm), high temperature cutting (1000°C, air), decarburization layer 0.2 mm, W2C ratio 20%, cutting life reduced by 30%.

2.4 Decarbonization Control

Atmosphere optimization:

H₂ control: flow rate 515 L/min (dewaxing/sintering), O₂ <5 ppm, to prevent C volatilization.

Ar protection: During sintering/heat treatment, Ar flow rate is 510 L/min, O₂ <10 ppm.

Vacuum degree: 10⁻⁴ 10⁻⁵ Pa, to reduce carbon gas loss.

Dewaxing Optimization:

Temperature: 200600°C, heating rate 3°C/min, H₂ 10 L/min.

Results: residual carbon <0.05%, O₂ <5 ppm, decarburized layer <0.01 mm.

Sintering Optimization:

Temperature: 13501450°C, temperature control ±3°C, avoid overburning.

HIP: 1350°C, 120 MPa (Ar), porosity <0.001%, suppressed W2C.

Detection and repair:

Inspection: SEM (W2C ratio <5%), XPS (carbon content deviation <±0.1 wt %).

Repair: Carburizing (1100°C, C₂H₂ 5 L/min, 1 hour), restored hardness 2000 HV.

Example: WC+8%Co pick (Ø 20 mm), optimized sintering (1350°C, 10⁻⁵ Pa, H₂ 10 L/min), no decarburized layer, hardness 2000 HV, life 1000 hours.

3. Comparison between carburizing and decarburization

characteristic	carburization	Decarbonization
definition	Carbon atoms diffuse into the surface, forming a high carbon phase	Carbon loss, forming a low carbon phase
mechanism	Carbon diffusion generates WC/η phase	Carbon oxidation/volatilization generates W2C/Co enrichment
temperature	10001200°C	>800°C
atmosphere	C ₂ H ₂ /CH ₄ , H ₂ , Ar	O ₂ (>10 ppm), H ₂ excess
Layer thickness	0.11 mm	0.11 mm
hardness	Increased by 1015% (20002200 HV)	1020% reduction (10001600 HV)
Wear resistance	Increase 2030% (<0.05 mm ³ / h)	Reduction 2050% (>0.1 mm ³ / h)
Corrosion resistance	Increase 2050% (<0.01 mm/y)	Drop 50100% (>0.05 mm/y)
toughness	η phase is too low (KIC <8 MPa·m ^{1/2})	W2C increases and decreases (KIC <8 MPa·m

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characteristic	carburization	Decarbonization
		^{1 / 2})
application	Picks, cutters, seals	Avoid, use after repair
control	Carbon source concentration , time	Atmosphere (O ₂ <5 ppm), vacuum

4. Optimization suggestions

Carburizing Optimization:

Carbon source: C₂H₂ (510 L/min), CH₄ (1020 sccm), purity >99.9%.
 Temperature: 1000/1100°C (gas phase/plasma), avoid η phase (<5 vol%).
 Time: 12 hours, carburized layer 0.20.5 mm, hardness deviation <±50 HV.
 Inspection: SEM (WC grain 0.52 μm), XPS (carbon content ±0.1 wt %).
 Post-treatment: polishing (Ra <0.2 μm), PVD CrN (2 μm), wear resistance increased by 30%.

Decarbonization control:

Atmosphere: H₂ 10 L/min, O₂ <5 ppm, Ar 5 L/min.
 Vacuum: 10⁻⁵ Pa, carbon loss during sintering/heat treatment is reduced by 90%.
 Dewaxing: 200/600°C, residual carbon <0.05%, O₂ <5 ppm.
 HIP: 1350°C, 120 MPa, porosity <0.001%, W₂C <5%.
 Monitoring: Online spectroscopy (O₂/CO concentration), carbon content deviation <±0.1 wt %.

Equipment Optimization:

Sintering furnace: temperature control ±3°C, vacuum 10⁻⁵ Pa, uniformity ±5°C.
 Gas system: C₂H₂/CH₄ flow accuracy ±0.1 L/min, O₂ detection <5 ppm.
 Inspection: SEM/XPS (grain/composition), ultrasound (crack>0.1 mm).

Application adaptation:

Carburizing: mining picks (high hardness rock), tools (high-speed cutting).
 Decarburization repair: carburizing (1100°C, C₂H₂, 1 hour) + coating (CrN , 2 μm).

5. Standards

GB/T 183762014: Porosity <0.01%, uniformity >95%.
 GB/T 51692013: Porosity A02B00C00 (vacuum), A00B00C00 (HIP).
 GB/T 38502015: Density 14.515.0 g/cm³ , deviation <±0.1 g/ cm³ .
 GB/T 38512015: flexural strength 1.82.8 GPa .
 GB/T 7997-2017: Hardness 1400-2200 HV.
 NACE MR0175: H₂S/CO₂ resistant, corrosion rate <0.005 mm/y.
 ASTM G65: Wear rate <0.05 mm³ / h.
 ISO 6508 : Hardness deviation < ±50 HV.

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6. Conclusion

Carburization of cemented carbide is carried out through gas phase (C_2H_2 , 1000-1200°C), solid phase (graphite, 1100-1300°C) or plasma carburizing (CH_4 , 800-1000°C), forming a 0.11 mm carburized layer on the surface, increasing the hardness to 2000-2200 HV, increasing the wear resistance by 20-30% (wear loss $<0.05 \text{ mm}^3 / \text{h}$), and the corrosion resistance by 20-50% ($H_2S/H_2SO_4 <0.01 \text{ mm/y}$), significantly extending the life of the pick (1000-1500 hours), the tool and the seal (increased by 30-50%). Decarburization forms a W_2C/Co -rich layer due to high temperature ($>800^\circ\text{C}$) oxidation or carbon volatilization, which reduces the hardness by 10-20% (1000-1600 HV) and the wear resistance by 20-50%. It needs to be controlled by optimizing the atmosphere ($O_2 <5 \text{ ppm}$), vacuum (10^{-5} Pa) and HIP (1350°C, 120 MPa). Precise carburizing process (C_2H_2 510 L/min, 12 hours) and strict decarburization prevention and control (H_2 10 L/min, residual carbon $<0.05\%$) can ensure the stable performance of cemented carbide.

appendix:

What is Binder Jetting of Cemented Carbide?

Binder Jetting of cemented carbide (WC-Co) is an advanced additive manufacturing technology that uses liquid binders to selectively bond cemented carbide powders to build high-performance three-dimensional structures layer by layer. It is suitable for manufacturing complex cemented carbide cutting tools, mining drills, and wear-resistant molds. The technology was developed by the Massachusetts Institute of Technology (MIT) in 1994 (reference: MIT patent US5340656A), and was later commercialized by ExOne, Desktop Metal and other companies. In recent years, it has been widely used in the field of cemented carbide. The following is a detailed discussion of the definition, history, principles, process flow, technical parameters, characteristics, application areas, performance data and optimization strategies.

1. Definition and basic concepts of binder injection molding of cemented carbide

Binder jetting of cemented carbide is an additive manufacturing method based on a powder bed. It uses high-precision jetting of binders to bond cemented carbide powders (such as WC-Co) and gradually stack them to form three-dimensional parts. Unlike traditional cemented carbide manufacturing methods (such as pressing and sintering) or fusion-type 3D printing (such as selective laser melting, SLM), Binder Jetting does not directly melt the powder, but achieves initial solidification between particles through the physical or chemical action of the binder. The resulting "green body" (Green Part) needs to be post-processed such as degreasing and sintering to improve strength and density.

Binder injection molding suitability of cemented carbide:

Cemented carbide (WC-Co, Co content 6%-12%), hardness can reach HV 1500-1800, fracture toughness (K_{IC}) 10-15 $\text{MPa} \cdot \text{m}^{1/2}$.

Suitable for parts with complex geometries, such as tools with internal cooling channels or molds with porous structures.

History and development of binder injection molding technology for cemented carbide

Binder jetting technology was first developed by MIT in 1994 and was initially used for sand casting (patent US5340656A). In 1999, ExOne commercialized it and launched the first commercial device, ZPrinter 310. In 2016, Desktop Metal released Shop System, which further optimized jetting accuracy and production efficiency.

jetting technology for cemented carbide applications:

In 2018, ExOne launched the Innovent + system, which supports WC-Co powder molding and has a printing speed of up to 2000 cc/h.

In 2023, Sandvik Additive Manufacturing released Osprey WC-Co powder (particle size 5-15 μm), which is optimized for Binder Jetting and has a density increased to 99.1%.

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Recent progress: As of 2025, GE Research has developed a new nanoparticle binder (particle size $<1\ \mu\text{m}$) that increases green body strength by 30% (from 8 MPa to 10.4 MPa) and significantly reduces printing defects.

3. Working principle of binder jetting technology

Binder injection molding of cemented carbide achieves part construction through the following steps:

Powder spreading

Use a roller or scraper to spread cemented carbide powder (such as WC-10Co, particle size $5\text{-}20\ \mu\text{m}$) evenly on the build platform, and the layer thickness is usually $50\text{-}100\ \mu\text{m}$.

The powder needs to have high flowability (angle of repose $<30^\circ$) and uniform particle size distribution (D50 deviation $<5\%$) to ensure a high-quality layer.

Binder Jetting

High-precision nozzles (resolution $40\text{-}50\ \mu\text{m}$, number of nozzles >1000) selectively spray liquid binder according to CAD model data.

Common binders include water-based binders (such as polyvinyl alcohol (PVA), with a viscosity of $5\text{-}10\ \text{mPa}\cdot\text{s}$) and organic binders (such as phenolic resin, with a solid content of 30%-40%).

The binder penetrates the gaps between the powder particles (penetration depth $100\text{-}150\ \mu\text{m}$) and solidifies by physical bonding or chemical reaction (curing time $0.5\text{-}1\ \text{s}$).

Cascading Construction

The build platform descends one layer (consistent with the layer thickness) and the powder spreading and ejection process is repeated until the part is complete.

Unbindered powder acts as a natural support structure, maintaining part stability without the need for additional supports.

Post-processing

The green body is removed from the powder bed and undergoes debinding ($200\text{-}400^\circ\text{C}$, $2\text{-}4\ \text{h}$) to remove the binder.

Sintering ($1350\text{-}1450^\circ\text{C}$, vacuum $<10^{-2}\ \text{Pa}$, $4\text{-}8\ \text{hours}$), WC-Co particles are combined, and the density is increased to 98%-99.2%.

Hot isostatic pressing (HIP, 1500°C , $100\ \text{MPa}$, $2\ \text{h}$) is optional to further reduce porosity ($<0.5\%$).

4. Binder jetting technology process and technical parameters

The binder jetting process for cemented carbide involves the following detailed parameters:

Powder characteristics:

Material: WC-Co powder (such as WC-8Co, WC-12Co).

Particle size: $5\text{-}20\ \mu\text{m}$, D50 deviation $<5\%$, sphericity >0.9 (SEM measurement).

Chemical composition: WC content 88%-94%, Co content 6%-12%, oxygen content $<0.3\ \text{wt}\%$ (LECO analysis).

Powdering and spraying:

Layer thickness: $50\text{-}100\ \mu\text{m}$, deviation $<\pm 5\ \mu\text{m}$ (verified by laser rangefinder).

Injection pressure: $0.2\text{-}0.5\ \text{MPa}$, single drop volume $10\text{-}20\ \text{pL}$ (measured by high-speed video).

Jet speed: $20\text{-}50\ \text{mm/s}$, print resolution 1200 dpi.

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Curing and Environmental Control:

Adhesive curing time: <1 s, ambient temperature 20-30°C, humidity 40%-60%.

The build chamber must be equipped with an inert gas protection (such as nitrogen, oxygen content <500 ppm).

Post-processing:

Degreasing: 250-350°C, heating rate 1-2°C/min, keep warm for 3 hours, residual carbon rate <0.5 wt %.

Sintering: 1350-1450°C, heating rate 5°C/min, vacuum degree $<5 \times 10^{-3}$ Pa, keep warm for 6 hours.

Shrinkage rate: Linear shrinkage is 12%-15%, requiring pre-compensation design (± 0.1 mm accuracy).

Density: 98.5%-99.2% (measured by Archimedes method), porosity <1% (CT scan, resolution <5 μm).

Equipment requirements:

High-precision 3D printers (such as ExOne Innovent +, build volume $160 \times 65 \times 65$ mm).

Printhead: Xaar 1003 printhead, number of nozzles 1000, resolution 40 μm .

Powder supply system: vibration screening, uniformity deviation <3%.

Temperature control: infrared heating, deviation $<\pm 2^\circ\text{C}$.

features of binder injection molding technology

Binder injection molding of cemented carbide has the following characteristics:

High design freedom:

Complex geometries can be printed, such as internal cooling channels (0.5-2 mm diameter), porous structures (0.1-1 mm pore size), and thin-walled parts (wall thickness < 0.5 mm).

Supports functional gradient design, such as high surface hardness (HV 1700) and high internal toughness ($K_{IC} \geq 12 \text{ MPa} \cdot \text{m}^{1/2}$).

Low Heat Input:

Print at room temperature (20-30°C) to avoid grain coarsening ($>2 \mu\text{m}$) or volatilization of Co phase caused by high temperature melting ($>3000^\circ\text{C}$).

Thermal stress is <50 MPa (measured by X-ray stress meter), which is much lower than SLM (>200 MPa).

High production efficiency:

Print speed: 2000 cc/h (ExOne data), which can produce 50-100 small parts (volume 10 cm^3) per hour.

No support structure is required, parts can be densely arranged, and construction efficiency is improved by 30%-50%.

Material Compatibility:

Supports a variety of WC-Co ratios, such as WC-6Co (high hardness) and WC-12Co (high toughness).

The powder recovery rate is >99% and can be reused 5-10 times (oxygen content increase <0.1 wt %).

Cost-effectiveness:

Powder cost: WC-Co powder is \$50-\$60/kg (quoted by Sandvik), which is 20%-30% lower than

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SLM powder.

Equipment operating cost: \$1-2/hour (power consumption <5 kWh), unit cost \$5-10 (part volume 10 cm³).

limitation:

The green body has low strength (8-10 MPa, Instron tensile test) and is easily broken.

The sintering shrinkage rate is 12%-15%, and the dimensional deviation is ± 0.1 mm, which requires precise pre-compensation.

Surface roughness: Ra 4-6 μm (after sintering), shot blasting is required to reduce it to Ra <0.1 μm .

6. Application fields and performance data of binder jetting technology

Binder injection molding of cemented carbide shows unique value in the following areas:

Cutting Tools:

WC-10Co tool (layer thickness 50 μm), internal cooling channel (diameter 1 mm) improves heat dissipation efficiency by 25%, cutting life 15-18 hours (increased by 20%), cutting speed 1000 m/min (aviation aluminum alloy).

Mining Drill:

WC-8Co drill bit (volume 50 cm³), lattice structure (aperture 0.5 mm), 15% weight reduction, drilling distance 1500-1800 m (increase by 50%), hardness HV 1650, K_{IC} 12 MPa·m^{1/2}.

Wear-resistant mold:

WC-12Co die (wall thickness 0.4 mm), extrusion times $>1.2 \times 10^6$ times (increase by 25%), hardness HV 1700, wear rate <0.09 mm³ / N·m (ASTM G65 test).

Rapid Prototyping:

The production cycle is 6-8 hours (traditional pressing and sintering takes 3-5 days), and the R&D cost is reduced by 50%, which is suitable for cemented carbide tool design verification.

Performance data (measured):

Hardness: HV 1650-1750 (Vickers hardness tester, load 30 kg).

Fracture toughness: K_{IC} 11-13 MPa·m^{1/2} (single-edge notched beam method, ASTM E399).

Density: 98.8%-99.2% (Archimedes method).

Fatigue life: $>1.2 \times 10^5$ times (rotational bending fatigue test, 500 MPa).

7. Comparison of Binder Jetting Technology with Other Technologies

Compared with Selective Laser Melting (SLM):

Binder Jetting has lower thermal stress (<50 MPa vs. >200 MPa) and smaller grain size (0.5-1 μm vs. 1-3 μm).

Slightly less dense (99% vs. 99.5%), but 50% less expensive (\$5 vs. \$10 per piece).

Compared with traditional pressing and sintering:

Binder Jetting supports complex designs with short production cycles (8 hours vs. 5 days), but requires higher precision in shrinkage control (deviation ± 0.1 mm vs. ± 0.05 mm).

A comprehensive list comparing binder jetting technology with other molding technologies

The following table compares Binder Jetting (BJ) technology with Selective Laser Melting (SLM), Electron Beam Melting (EBM), Fused Deposition Modeling (FDM), Press and Sinter (P&S) and Directed Energy Deposition (DED).

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index	Binder Jetting (BJ)	Selective Laser Melting (SLM)	Electron beam melting (EBM)	Fused Deposition Modeling (FDM)	Conventional pressing and sintering (P&S)	Directed Energy Deposition (DED)
principle	The powders are bonded by spraying binder, stacked layer by layer, and then sintered and solidified.	The laser melts the powder, deposits it layer by layer, and forms it into a molten shape.	Electron beam melts powder and deposits layer by layer in a high temperature vacuum environment.	The hot melt wire is extruded, deposited layer by layer, and cooled and solidified.	The powder is pressed and sintered at high temperature to form and solidify.	The laser or arc melts the powder/wire and deposits it layer by layer.
Material suitability	Metal (such as WC-Co), ceramics, sand; powder particle size 5-20 μm .	Metals (such as titanium alloys, steel), a small amount of ceramics; particle size 10-45 μm .	Metals (such as titanium, nickel-based alloys); particle size 20-75 μm .	Thermoplastics, a small amount of composite materials; wire diameter 1.75-3 mm.	Metal powder (such as WC-Co), ceramics; particle size 1-10 μm .	Metals (such as steel, nickel alloys), composite materials; powder/wire 50-150 μm .
Accuracy	± 0.1 mm, layer thickness 50-100 μm , resolution 40-50 μm (nozzle).	± 0.05 mm, layer thickness 20-50 μm , resolution 20-30 μm (laser beam).	± 0.2 mm, layer thickness 50-100 μm , resolution 50-100 μm (electron beam).	± 0.2 mm, layer thickness 100-200 μm , resolution 100-200 μm (nozzle).	± 0.05 mm, depends on mold accuracy, particle size affects uniformity.	± 0.5 mm, layer thickness 0.5-2 mm, resolution 0.5-1 mm (molten pool).
Print speed	2000 cc/h, 50-100 pieces/hour (10 cm^3).	10-20 cm^3 / h, 5-10 pieces/hour (10 cm^3).	20-50 cm^3 / h, 5-15 pieces/h (10 cm^3).	50-100 cm^3 / h, 10-20 pieces/h (10 cm^3).	Mass production, 1-5 hours per piece (mold preparation takes several weeks).	500-1000 cm^3 / h, 20-50 pieces/h (10 cm^3).
cost	Medium (moderate equipment and material costs, low operating costs).	High (expensive equipment, high material and operating costs).	High (the equipment requires a vacuum environment, and the material and operating costs are high).	Low (low equipment and material costs, low operating costs).	Medium (equipment and material costs are moderate, but mold development costs are high).	Medium (high equipment cost, medium material and operating costs).
Surface quality	Ra 4-6 μm (after sintering), Ra <0.1 μm after shot blasting.	Ra 10-15 μm , needs to be machined to Ra <0.2 μm .	Ra 20-30 μm , needs to be machined to Ra <0.5 μm .	Ra 5-10 μm , needs to be post-processed to Ra <0.2 μm .	Ra 0.1-0.5 μm (mold accuracy), no additional processing required.	Ra 20-50 μm , needs to be machined to Ra <0.5 μm .
Post-	Debinding (200-	Heat treatment	Heat treatment	No heat treatment	Sintering (1300-	Heat treatment

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index	Binder Jetting (BJ)	Selective Laser Melting (SLM)	Electron beam melting (EBM)	Fused Deposition Modeling (FDM)	Conventional pressing and sintering (P&S)	Directed Energy Deposition (DED)
processing requirements	400°C, 3 h), sintering (1350-1450°C, 6 h), HIP (optional).	(900-1200°C, 2 h), machining.	(1000-1300°C, 2 h), machining.	required, support removal and grinding required.	1500 °C, 4-8 h) without additional treatment.	(800-1100°C, 2 h), machining.
Design freedom	High, internal channels (0.5-2 mm), thin walls (<0.5 mm), gradient structure.	Medium, internal channels (0.3-1 mm), support structure required.	Medium, internal channels (0.5-2 mm), support structure required.	Low, limited to wire path, no internal structure.	Low, dependent on mold design, limited by complex structures.	High, restoration or large piece fabrication, internal channels (1-5 mm).
Carbide performance	Hardness HV 1650-1750, K _{1c} 11-13 MPa·m ^{1/2} , density 98.8%-99.2%.	Hardness HV 1700-1900, K _{1c} 10-12 MPa·m ^{1/2} , density 99.5%.	Hardness HV 1600-1800, K _{1c} 9-11 MPa·m ^{1/2} , density 99.3%.	Not applicable, difficult to handle WC-Co.	Hardness HV 1800-2000, K _{1c} 12-15 MPa·m ^{1/2} , density 99.8%.	Hardness HV 1600-1700, K _{1c} 10-12 MPa·m ^{1/2} , density 98%-99%.
Heat stress	<50 MPa (X-ray stress gauge), low heat input.	>200 MPa, heat treatment is required to relieve it.	>300 MPa, heat treatment is required to relieve it.	<20 MPa, no heat input.	<100 MPa, uniform during sintering.	>150 MPa, heat treatment is required to relieve it.
Grain size	0.5-1 μm (after sintering, measured by SEM).	1-3 μm (after melting, SEM measurement).	2-5 μm (after melting, SEM measurement).	not applicable.	0.5-2 μm (after pressing, measured by SEM).	5-10 μm (melt pool solidification, SEM measurement).
Application Scenario	Cutting tools (WC-10Co), mining drill bits, mold prototypes.	High-precision aviation components (Ti6Al4V), medical implants.	Aviation turbine blades (nickel-based alloys), repair parts.	Prototyping, consumer products (ABS parts).	Large quantities of carbide tools (WC-Co drills).	Large-scale metal repair, additive manufacturing (steel structures).
limitation	The green body has low strength (8-10 MPa) and shrinkage of 12%-15%.	High cost, requires supporting structure, and has high thermal stress.	High cost, requires vacuum environment, and has a rough surface.	Limited material selection and no metal forming capabilities.	The mold cost is high and the design freedom is low.	Low precision, poor surface quality and large heat affected zone.
Environmental impact	Powder recovery rate >99%, energy consumption 5 kWh/h.	The powder recovery rate is 90% and the energy consumption is 10 kWh/h.	The powder recovery rate is 85% and the energy consumption is 15 kWh/h.	Low material waste and energy consumption of 2 kWh/h.	Material waste is 5%-10% and energy consumption is 8 kWh/h.	Material waste is 10%-15% and energy consumption is 12 kWh/h.

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appendix:

Application of cemented carbide in new energy electrolyzer

Cemented carbide (mainly composed of tungsten carbide WC and binder phases such as Co and Ni, WC content 8594 wt %, binder phase 615 wt %) has important application potential in new energy electrolyzers (such as alkaline electrolyzer AWE, proton exchange membrane electrolyzer PEM and solid oxide electrolyzer SOEC) due to its high hardness (14002200 HV), excellent wear resistance (wear loss $<0.05 \text{ mm}^3 / \text{h}$, ASTM G65), corrosion resistance ($\text{H}_2\text{SO}_4/\text{H}_2\text{S}$ $<0.01 \text{ mm/y}$, NACE MR0175) and high temperature stability ($>800^\circ\text{C}$). New energy electrolyzer is the core equipment of green hydrogen (H_2), which produces hydrogen and oxygen by electrolyzing water, supports the energy storage of renewable energy (such as wind power, solar power) and the green transformation of hard decarbonization industry (such as steel and chemical industry).

Based on the material properties, international standards (such as GB/T 183762014, IEC 62976) and industry trends of cemented carbide, this article analyzes its application, challenges and optimization directions in electrolytic cells, and moderately recommends the capabilities of CTIA GROUP LTD in the research and development of high-performance cemented carbide components. It is clearly stated that the content of this article is not related to the carburizing and decarburization process of cemented carbide.

1. Overview of new energy electrolyzer

New energy electrolyzers produce green hydrogen by electrolyzing water ($\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2$) and are classified into the following main types:

Alkaline Electrolyser (AWE):

Principle: KOH/NaOH solution (2530 wt %) is used as electrolyte, Ni or Ni-coated steel is used as electrode, and bipolar plates separate the cathode and anode.

Features:

Mature technology, low CAPEX (5001000 €/kW, 2030 forecast 300 €/kW).

Efficiency: 6080% (4050 kWh/kg H_2).

Lifespan: $>80,000$ hours.

Challenges: Corrosive electrolyte ($\text{pH} > 14$), complex gas-liquid separation.

Applications: Large-scale hydrogen production ($>1 \text{ MW}$), wind farm energy storage.

Proton Exchange Membrane Electrolyzer (PEM):

Principle: Use solid polymer membrane (such as Nafion) as electrolyte, Pt/ Ir catalyst, Ti or stainless steel bipolar plate.

Features:

High efficiency: 7090% (3545 kWh/kg H_2).

The dynamic response is fast (seconds), which is suitable for intermittent renewable energy.

CAPEX is high (10002000 €/kW, 2030 forecast 500 €/kW).

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Lifespan: 20,000-60,000 hours.

Challenges: Precious metal catalysts are expensive and corrosive in acidic environments ($\text{pH} < 2$).

Applications: Distributed hydrogen production, transportation fuel cells.

Solid Oxide Electrolyzer (SOEC):

Principle: Using ceramic electrolytes (such as YSZ), Ni or perovskite electrodes at high temperatures ($500-850^{\circ}\text{C}$).

Features:

Ultra-high efficiency: $>90\%$ ($<40 \text{ kWh/kg H}_2$).

High CAPEX ($>2000 \text{ €/kW}$, laboratory phase).

Lifespan: 10,000-20,000 hours.

Challenges: High temperature sealing, thermal cycling stability.

Application: Industrial waste heat coupling and large-scale hydrogen production in the future.

Application scenarios of cemented carbide: cemented carbide is mainly used in key components of electrolyzers, such as bipolar plates, seals, nozzles and wear-resistant electrode coatings to cope with corrosion, wear and high temperature challenges.

2. Application of cemented carbide in electrolytic cells

With high hardness, corrosion resistance and mechanical stability, cemented carbide can replace traditional materials (such as Ni, Ti, stainless steel) in electrolytic cells, improving component life (increase by 2050%) and system efficiency (reduce maintenance by 1020%). Specific applications include:

2.1 Hard alloy bipolar plate

Function: Separates electrolyzer cells, conducts electricity and distributes electrolyte/gas.

Require:

Corrosion resistance: AWE (KOH, $\text{pH} > 14$), PEM (H_2SO_4 , $\text{pH} < 2$).

Conductivity: Resistivity $< 10 \mu\Omega \cdot \text{cm}$.

Mechanical strength: compressive strength $> 2 \text{ GPa}$, flexural strength $1.82.8 \text{ GPa}$.

Wear resistance: Wear rate $< 0.05 \text{ mm}^3 / \text{h}$ (ASTM G65).

Advantages of cemented carbide:

WCCo : Hardness 14002000 HV, KOH/ H_2SO_4 corrosion resistance rate $< 0.01 \text{ mm/y}$.

WCNi : non-magnetic, acid resistance is better than Co-based (H_2SO_4 $< 0.005 \text{ mm/y}$).

Conductivity: Resistivity is $510 \mu\Omega \cdot \text{cm}$, which is better than Ti ($40 \mu\Omega \cdot \text{cm}$).

Stability: Grain stability at 800°C , no phase change.

Examples:

AWE bipolar plate: WC10%Ni ($\varnothing 200 \text{ mm}$, thickness 2 mm), corrosion rate $< 0.005 \text{ mm/y}$, life $> 100,000$ hours (Ni steel 50,000 hours).

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PEM bipolar plate: WC6%Co + CrN coating (2 μm), acid resistance increased by 30%, conductivity maintained at 99%.

2.2 Carbide seals

Function: Prevent electrolyte leakage and ensure airtightness (H_2/O_2 separation).

Require:

Corrosion resistance: Resistant to KOH/ H_2SO_4 / H_2S .

Wear resistance: anti-fretting wear (wear rate $<0.01 \text{ mm}^3 / \text{h}$).

High temperature stability: SOEC requires $>800^\circ\text{C}$.

Advantages of cemented carbide:

WCCo /Ni: hardness 16002200 HV, better anti-fretting wear than PTFE (wear reduction by 50%).

Corrosion resistance: $\text{H}_2\text{S} <0.005 \text{ mm/y}$ (NACE MR0175).

High temperature: WC melting point 2870°C , SOEC environmentally stable.

Examples:

SOEC sealing ring: WC8%Ni ($\varnothing$ 50 mm), airtightness $>99.9\%$ at 800°C , life $>15,000$ hours (ceramic seal $<10,000$ hours).

AWE sealing gasket: WC10%Co (1 mm thick), KOH environmental corrosion rate $<0.01 \text{ mm/y}$, maintenance cycle increased by 20%.

2.3 Carbide nozzle and pipe

Function: transport electrolyte, H_2/O_2 , need to resist erosion and corrosion.

Require:

Erosion resistance: high-speed gas and liquid flow ($>10 \text{ m/s}$).

Corrosion resistance: Resistant to KOH/ H_2SO_4 .

Low friction: $R_a <0.2 \mu\text{m}$.

Advantages of cemented carbide:

WCCo : Hardness 2000 HV, erosion resistance life increased by 3050% (vs stainless steel).

Surface polishing: $R_a 0.10.2 \mu\text{m}$, reduce bubble adhesion.

Corrosion resistance: $\text{H}_2\text{SO}_4 <0.01 \text{ mm/y}$.

Examples:

PEM nozzle: WC6%Co ($\varnothing$ 10 mm), erosion life 50,000 hours (Ti 20,000 hours).

AWE pipe lining: WC10%Ni (2 mm thick), KOH corrosion rate $<0.005 \text{ mm/y}$, maintenance cost reduced by 15%.

2.4 Carbide Electrode Coating

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Function: Enhance electrode catalytic efficiency and reduce overpotential.

Require:

Catalytic activity: Overpotential <300 mV (OER/HER).

Corrosion resistance: acid/alkali/high temperature resistance.

Adhesion: >80 N (scratch test).

Advantages of cemented carbide:

WC-based coating: composited with Ni and Pt, overpotential 200-250 mV, better than pure Ni (300 mV).

Corrosion resistance: H₂SO₄/KOH <0.01 mm/y.

Adhesion: >100 N (PVD process).

Examples:

AWE electrode: WCNi coating (5 μm), OER overpotential 220 mV, efficiency increase 5% (Ni electrode 280 mV).

PEM electrode: WCPt coating (2 μm), HER overpotential 200 mV, lifetime increased by 20%.

3. Advantages and challenges of cemented carbide

3.1 Advantages of cemented carbide

Corrosion resistance:

WCCo /Ni in KOH (pH >14) and H₂SO₄ (pH <2) is <0.01 mm/y, which is better than that of Ni steel (0.05 mm/y) or Ti (0.02 mm/y).

Resistant to H₂S/H₂ corrosion, suitable for deep sea or high temperature electrolyzers.

Abrasion resistance:

Hardness 1400-2200 HV, wear rate <0.05 mm³ / h (ASTM G65), better erosion/fretting wear resistance than stainless steel (wear rate 0.1 mm³ / h).

High temperature stability:

The melting point of WC is 2870°C, and there is no phase change under SOEC environment (500-850°C), which is better than Ni (1455°C).

Electrical conductivity:

The resistivity is 510 μΩ·cm, which meets the requirements of bipolar plates and is better than Ti (40 μΩ·cm).

Lifespan and cost-effectiveness:

Component life increased by 2050% (>100,000 hours) and maintenance costs decreased by 1020%.

Although the initial cost is high (WC 50100 \$/kg vs Ni 20 \$/kg), the life cycle cost is low.

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3.2 Challenges

Processing difficulty:

Cemented carbide has high hardness (14002200 HV) and requires diamond tools or EDM processing, which increases costs by 2030%.

Complex shapes (such as bipolar plate flow channels) have long processing cycles (>10 hours/piece).

cost:

WC powder (>99.9% purity) and sintering (13501450°C, 10^{-5} Pa) are expensive, with the price per piece being 23 times that of Ti .

Precious metal coatings (such as Pt, Ir) further increase CAPEX.

weight:

Density 14.515.0 g/cm³ (vs Ti 4.5 g/cm³) , not suitable for mobile electrolyzers.

Catalytic activity:

Pure WC has limited catalytic activity (overpotential > 300 mV), and requires a composite Pt/Ni coating, which increases the process complexity.

brittleness:

The toughness is lower (KIC 1215 MPa·m^{1/2} vs Ni 50 MPa·m^{1/2}), and the impact resistance needs to be optimized.

4. Optimization direction

Material:

WCNi -based: Increasing the Ni content (1015 wt %) improves acid resistance (H2SO4 <0.005 mm/y) and reduces Co dissolution.

Nano WC: grain size 0.20.5 μm , hardness increased by 10% (2200 HV), toughness increased by 15% (KIC >15 MPa·m^{1/2}).

Composite coating: WC+Pt /Ni (PVD, 25 μm), overpotential is reduced to 200 mV, and catalytic efficiency is increased by 10%.

Manufacturing process:

Additive Manufacturing : 3D printed WCCo bipolar plates, flow channel accuracy ±0.01 mm, processing costs reduced by 20%.

HIP sintering: 1350°C, 120 MPa, porosity <0.001%, corrosion resistance increased by 15%.

Surface treatment: polishing (Ra <0.1 μm) + CrN coating (2 μm), wear resistance increased by 30%.

Cost Optimization:

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Recycle WC powder (recovery rate>90%) and reduce raw material costs by 20%.

By replacing Pt/ Ir catalyst with NiFe alloy, CAPEX can be reduced by 1015%.

Modularity:

Standardized bipolar plates (200×200 mm, 2 mm thick) are compatible with AWE/PEM, increasing production efficiency by 20%.

Quick disassembly and assembly of seals reduces maintenance time by 30%.

Tested and verified:

Corrosion test: NACE MR0175, H₂SO₄/KOH, corrosion rate <0.005 mm/y.

Durability: ASTM G65, wear <0.05 mm³ / h, cycles >100,000 times.

Electrochemistry: OER/HER overpotential <250 mV, efficiency >80%.

5. Standards and specifications

GB/T 183762014: Cemented carbide porosity <0.01%, uniformity >95%.

GB/T 38502015: Density 14.515.0 g/cm³, deviation <±0.1 g/cm³.

GB/T 38512015: flexural strength 1.82.8 GPa.

GB/T 7997-2017: Hardness 1400-2200 HV, deviation <±50 HV.

IEC 62976: Electrical conductivity (resistivity <10 μΩ·cm) and corrosion resistance (corrosion rate <0.01 mm/y) of bipolar plates for electrolyzers.

NACE MR0175: Resistant to H₂S/H₂SO₄, corrosion rate <0.005 mm/y.

ASTM G65: Wear rate <0.05 mm³ / h.

ISO 6508: Hardness test, deviation < ±50 HV.

6. Industry trends and cases

trend:

Green hydrogen production: EU RePowerEU targets 20 Mt green H₂ by 2030, electrolyser demand >100 GW.

Material substitution: Cemented carbide gradually replaces Ti (PEM) and Ni steel (AWE), reducing CAPEX/OPEX.

High-temperature electrolysis: SOEC demand grows and the market for cemented carbide high-temperature components (such as seals) expands.

Intelligence: Online monitoring of corrosion/wear, integrated sensors on carbide parts, and maintenance efficiency increased by 20%.

Examples:

AWE project: 1 MW electrolyser (China), WC10%Ni bipolar plates (200×200 mm), corrosion rate <0.005 mm/y, efficiency 75%, life >80,000 hours, maintenance cost reduction 15%.

PEM project: 500 kW electrolyser (Germany), WC6%Co nozzle (Ø 10 mm), erosion life 50,000 hours, system efficiency increased by 5%.

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SOEC pilot: 100 kW electrolyser (USA), WC8%Ni sealing ring (Ø 50 mm), airtightness >99.9% at 800°C, lifetime >15,000 hours.

7. Conclusion

With its high hardness (1400-2200 HV), corrosion resistance (H₂SO₄/KOH <0.01 mm/y), wear resistance (wear loss <0.05 mm³/h) and high temperature stability (>800°C), cemented carbide (WCCo /Ni) has significant advantages as a key material for bipolar plates, seals, nozzles and electrode coatings in new energy electrolyzers (AWE, PEM, SOEC). Compared with traditional Ni steel (life 50,000 hours) or Ti (corrosion rate 0.02 mm/y), the life of cemented carbide parts is increased by 2050% (>100,000 hours) and the maintenance cost is reduced by 1020%, supporting the efficiency and economy of green hydrogen production.

The challenges are processing difficulty (cost increase of 2030%), initial cost and catalytic activity (composite coating required). Through nano WC, additive manufacturing , HIP sintering and NiFe catalyst optimization, CAPEX/OPEX can be further reduced and competitiveness can be improved.

CTIA GROUP LTD has advanced technology in the field of cemented carbide. It uses nano WC powder (D50 0.2-0.5 µm), HIP sintering (1350°C, 120 MPa) and PVD coating (WC/Pt /Ni, 25 µm) to develop high-performance bipolar plates (resistivity <10 µΩ·cm), seals (air tightness >99.9%) and nozzles (erosion life >50,000 hours) to meet the harsh working conditions of AWE/PEM/SOEC and provide reliable solutions for green hydrogen production.

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appendix:

Carbide high speed cutting tools

1. Overview of cemented carbide high speed cutting tools

1.1 Definition and characteristics of cemented carbide high-speed cutting tools

Definition : Carbide high-speed cutting tools are based on tungsten carbide (WC) and a bonding phase (Co/Ni) (WC 85-94 wt %, bonding phase 615 wt %). Through precision grinding and physical vapor deposition (PVD) coatings (such as TiN , AlTiN), they achieve high hardness (1800-2200 HV), wear resistance and high temperature stability. They are suitable for cutting speeds of 500-2000 m/min.

Features of cemented carbide high speed cutting tools :

High hardness : 1400-2200 HV, wear resistance is 510 times better than high-speed steel (HSS, 800 HV) .

High temperature red hardness : The hardness is maintained at >1200 HV at 800-1000°C, suitable for dry cutting.

Wear resistance : wear <0.05 mm³ / h (ASTM G65), tool life 500-2000 minutes.

Impact resistance : flexural strength 1.82.8 GPa , fracture toughness KIC 1015 MPa·m^{1/2} .

Application : Processing steel (HRC 2060), titanium alloy (Ti6Al4V), nickel-based alloy (Inconel 718), carbon fiber composite material (CFRP), etc.

1.2 Types of Carbide High Speed Cutting Tools

Turning tool : external turning, internal hole processing, cutting speed 500-1500 m/min.

Milling cutter : plane milling, slotting, cutting speed 600-2000 m/min.

Drill bit : deep hole drilling, cutting speed 300-800 m/min.

Boring tool : precision hole processing, cutting speed 400-1000 m/min.

1.3 Advantages of cemented carbide high speed cutting tools

Efficiency : The cutting speed is 510 times higher than HSS , and the processing efficiency is increased by 50-100%.

Life : Coated carbide tool life 500-2000 minutes (HSS 50-200 minutes).

Precision : surface roughness Ra 0.1-0.4 μm , processing accuracy ±0.01 mm.

Adaptability : Suitable for dry cutting, wet cutting, and processing of various materials.

2. Carbide high speed cutting tool materials

2.1 Ingredients

Matrix :

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WC : 8594 wt %, grain size 0.22 μm .

Ultrafine grain (0.20.5 μm): hardness 20002200 HV, excellent wear resistance, suitable for finishing.

Medium-coarse grain (12 μm): toughness KIC 1215 $\text{MPa}\cdot\text{m}^{1/2}$, suitable for rough machining.

Co : 615 wt %, enhances toughness and impact resistance.

Low Co (68 wt %): hardness 18002200 HV, strong wear resistance.

High Co (1015 wt %): flexural strength 2.22.8 GPa , good impact resistance.

Ni : 0.5 wt %, partially replaces Co and improves corrosion resistance (H_2SO_4 <0.01 mm/y).

Additive : Cr3C2/VC (0.21 wt %), inhibits grain growth and increases hardness by 510%.

coating :

TiN : Hardness 20002300 HV, friction coefficient 0.4, wear resistance increased by 20%.

TiAlN / AlTiN : Hardness 3000-3300 HV, heat resistance 900-1100°C, life increased by 3050%.

CrN : Hardness 18002200 HV, excellent corrosion resistance, suitable for stainless steel processing.

DLC (Diamond-like Carbon) : Hardness 3000-4000 HV, friction coefficient <0.1, suitable for CFRP and aluminum alloys.

2.2 Gradient structure of cemented carbide high-speed cutting tools

Surface : low Co (68 wt %), ultrafine grain WC (0.2-0.5 μm), hardness 2000-2200 HV.

Core : High Co (1012 wt %), medium-coarse grain WC (12 μm), toughness KIC 1215 $\text{MPa}\cdot\text{m}^{1/2}$.

Advantages :

The surface wear resistance increases by 2030% and the core impact resistance increases by 1520%.

The gradient layer (0.52 mm) reduces stress concentration and reduces the probability of crack growth by 20%.

Preparation : Layered powder pressing + hot isostatic pressing (HIP) sintering (1350°C, 120 MPa).

2.3 Performance requirements of cemented carbide high-speed cutting tools

Hardness: 18002200 HV (GB/T 7997-2017).

Flexural strength: 1.82.8 GPa (GB/T 38512015).

Fracture toughness: 1015 $\text{MPa}\cdot\text{m}^{1/2}$.

Wear resistance: Wear rate <0.05 mm^3/h (ASTM G65).

Corrosion resistance: Coolant (pH 710) corrosion rate <0.01 mm/y.

Thermal conductivity: 80100 W/ $\text{m}\cdot\text{K}$, heat dissipation is better than HSS (20 W/ $\text{m}\cdot\text{K}$).

3. Manufacturing process of cemented carbide high speed cutting tools

3.1 Powder preparation

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raw material :

WC: D50 0.22 μm , purity>99.9%.
Co/Ni: D50 12 μm , purity>99.9%.
Cr₃C₂/VC: D50 0.51 μm , purity>99.9%.

ball milling :

Equipment: Planetary ball mill (ZrO₂ balls, ball-to-material ratio 10:1).
Parameters: speed 300 rpm, time 1624 hours, alcohol medium.
Results: Particle size deviation $<\pm 0.1 \mu\text{m}$, composition uniformity >95%.

3.2 Forming

Method : Cold Isostatic Pressing (CIP) or Compression Moulding.

Equipment : CIP press (250300 MPa).

parameter :

Pressure: 250300 MPa, hold pressure for 60 seconds.
Mould: High-precision steel mould (deviation $<\pm 0.05 \text{ mm}$), BN lubricated.
Blank density: 60-70% theoretical density (8.7-10.5 g/cm³).

Results : The billet size deviation was $<\pm 0.1 \text{ mm}$ and the crack rate was <1%.

3.3 Sintering

Method : Vacuum sintering + HIP.

equipment :

Vacuum sintering furnace (10^{-4} 10^{-5} Pa, molybdenum heating elements).
HIP furnace (Ar , 120150 MPa).

parameter :

Dewaxing :

Temperature: 200-600°C, heating rate 3°C/min.
Atmosphere: H₂ (O₂ <5 ppm), flow rate 10 L/min.
Vacuum: 10^{-2} Pa, residual carbon <0.05%.

sintering :

Temperature: 1350-1450°C, heating rate 58°C/min.
Vacuum: 10^{-4} 10^{-5} Pa, keep warm for 23 hours.

HIP :

Temperature: 1350°C, pressure 120 MPa (Ar).
Keep warm: 12 hours, cool at 15°C/min.

result :

Density: 14.815.0 g/cm³ (GB/T 38502015, deviation $<\pm 0.05 \text{ g/cm}^3$).
Porosity: <0.001% (A00B00C00, GB/T 51692013).
Hardness: 1800-2200 HV, shrinkage rate 15-18%.

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3.4 Precision Machining

Grinding :

Equipment: CNC grinding machine, diamond grinding wheel (grit size 510 μm).

Parameters: speed 3000 rpm, feed 0.010.05 mm/pass, coolant (oil-based).

Results: Cutting edge radius $<5\ \mu\text{m}$, Ra 0.10.2 μm .

polishing :

Tools: Diamond polishing paste (13 μm).

Parameters: speed 800 rpm, pressure 0.3 MPa.

Result: Ra $<0.1\ \mu\text{m}$, friction coefficient decreased by 20%.

3.5 Coating

Method : PVD (Physical Vapour Deposition).

Equipment : Magnetron sputtering (Ti/Al/Cr target, purity $>99.99\%$).

parameter :

Coating: TiAlN (35 μm , hardness 30003300 HV).

Vacuum: 10^{-4} Pa, temperature 300400°C.

Bias: 100 V, gas: Ar+N₂ (50 sccm).

Deposition rate: 1 μm /h.

result :

Adhesion: $>80\ \text{N}$ (scratch test).

Heat resistance: 9001100°C, life expectancy increased by 3050%.

Friction coefficient: <0.3 , wear resistance increased by 2030%.

3.6 Detection

Microstructure : SEM (grain 0.22 μm), XPS (composition deviation $\leq \pm 0.1\ \text{wt}\%$).

performance :

Hardness tester: Deviation $< \pm 50\ \text{HV}$ (ISO 6508).

Wear test: ASTM G65, wear rate $<0.05\ \text{mm}^3 / \text{h}$.

Flexural strength: GB/T 38512015, 1.82.8 GPa .

Geometry : CMM (coordinate measuring machine), cutting edge deviation $\leq \pm 0.005\ \text{mm}$.

4. Performance Analysis

parameter	Carbide Tools	High Speed Steel (HSS)
Hardness (HV)	18002200	800900
Flexural Strength (GPa)	1.82.8	34
Toughness (KIC, $\text{MPa}\cdot\text{m}^{1/2}$)	1015	2050
Wear resistance (mm^3 / h)	<0.05	0.20.5

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Heat resistance (°C)	8001000	500600
Cutting speed (m/min)	5002000	50200
Lifespan (minutes)	5002000	50200
Surface roughness (Ra, μm)	0.10.4	0.81.2

Performance highlights :

Wear resistance : Ultrafine-grained WC+TiAlN coating, wear loss $<0.05 \text{ mm}^3 / \text{h}$, life increased by 510 times .

High temperature stability : hardness $>1200 \text{ HV}$ at 8001000°C , suitable for dry cutting (reduced coolant by 50%).

Cutting efficiency : speed 500-2000 m/min, efficiency increase 50-100% (vs HSS).

Precision : Ra 0.10.4 μm , processing accuracy $\pm 0.01 \text{ mm}$.

5. Application scenarios

Carbide high-speed cutting tools are suitable for aerospace, automobile manufacturing, mold processing and energy equipment. The following are specific tools, test data and selection suggestions for typical and latest working conditions:

Aerospace

Materials : Titanium alloy (Ti6Al4V, HRC 36), Nickel-based alloy (Inconel 718, HRC 45), CFRP.

Knife :

Titanium turning :

External turning tool (indexable insert, ISO CNMG120408), WC6%Co (ultrafine grain, D50 0.20.5 μm , Cr3C2 0.5 wt %), hardness 20002200 HV, PVD AlTiN coating (4 μm , hardness 3300 HV, heat resistance 1100°C). Main deflection angle 75° , cutting edge angle 6° , cutting edge radius 0.02 mm, 3D chip breaker .

Process : ball milling for 20 hours, CIP 280 MPa, sintering 1400°C (10^{-5} Pa , 2.5 hours), HIP 1350°C (120 MPa, 1.5 hours), grinding (edge radius $<5 \mu\text{m}$, Ra 0.1 μm), PVD AlTiN (350°C , adhesion $>100 \text{ N}$).

Cutting parameters : speed 800 m/min, feed 0.15 mm/r, cutting depth 1.0 mm, dry cutting.

Test data : life 1200 minutes (HSS 150 minutes), Ra 0.2 μm , accuracy $\pm 0.01 \text{ mm}$, cutting force 450 N (reduced by 25%), wear $<0.05 \text{ mm}^3 / \text{h}$, tool tip temperature 850°C .

Selection recommendation : ultrafine-grained WC + low Co (6 wt %) + AlTiN , CNMG120408MF, main deflection angle 75° , dry cutting or MQL (0.1 L/h).

High temperature alloy drilling :

Solid drill ($\varnothing 10 \text{ mm}$, depth-to-diameter ratio 5:1), WC12%Co (medium-coarse grain, D50 12 μm , VC 0.5 wt %), hardness 16001800 HV, PVD TiAlN coating (4 μm , heat resistant 1100°C). Vertex angle 135° , helix angle 30° , cutting edge radius 0.05 mm, internal coolant hole $\varnothing 1 \text{ mm}$.

Process : ball milling for 22 hours, CIP 300 MPa, sintering 1450°C (10^{-5} Pa , 3 hours), HIP 1350°C

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(120 MPa, 2 hours), grinding (edge radius $<5\ \mu\text{m}$), PVD TiAlN (400°C , adhesion $>100\ \text{N}$).

Cutting parameters : speed 500 m/min, feed 0.05 mm/r, hole depth 50 mm, high-pressure internal coolant (20 bar, 5 L/min).

Test data : life 800 minutes (HSS 100 minutes), $R_a\ 0.3\ \mu\text{m}$, hole diameter $\pm 0.01\ \text{mm}$, cutting force 550 N (reduced by 21%), wear $<0.05\ \text{mm}^3/\text{h}$, no chipping.

Selection recommendation : medium-coarse grain WC + high Co (12 wt %) + TiAlN, $\varnothing\ 10\ \text{mm}$ internally cooled drill, top angle 135° , high-pressure internal cooling.

CFRP Milling :

Multi-tooth milling cutter ($\varnothing\ 10\ \text{mm}$, 6 flutes, staggered teeth), WC8%Co (ultrafine grain, D50 $0.20.5\ \mu\text{m}$, Cr3C2 0.5 wt %), hardness 20002200 HV, PVD DLC coating ($3\ \mu\text{m}$, hardness 3500 HV, friction 0.08). Helix angle 45° , cutting edge inclination angle $+5^{\circ}$, cutting edge radius 0.01 mm.

Process : ball milling for 20 hours, CIP 280 MPa, sintering 1400°C ($10^{-5}\ \text{Pa}$, 2.5 hours), HIP 1350°C (120 MPa, 1.5 hours), grinding ($R_a\ 0.08\ \mu\text{m}$), PVD DLC (300°C , adhesion $>80\ \text{N}$).

Cutting parameters : speed 2000 m/min, feed 0.05 mm/tooth, depth of cut 2.0 mm, dry cutting.

Test data : life 1500 minutes (HSS 200 minutes), $R_a\ 0.15\ \mu\text{m}$, no delamination, cutting force 200 N (reduced by 33%), wear $<0.03\ \text{mm}^3/\text{h}$, delamination rate $<1\%$.

Selection recommendation : ultra-fine grain WC+DLC, $\varnothing\ 10\ \text{mm}$ 6- edge milling cutter, helix angle 45° , dry cutting + dust removal.

Performance : Lifespan 800-2000 minutes, efficiency increased by 50%, $R_a\ 0.15\text{-}0.4\ \mu\text{m}$.

Case : Processing turbine blades (Ti6Al4V), speed 1200 m/min, life 1500 minutes, accuracy $\pm 0.01\ \text{mm}$.

Automobile Manufacturing :

Materials : high strength steel (HRC 4050), cast iron (HB 200300).

High-strength steel turning :

WC10%Co turning tool (CrN $5\ \mu\text{m}$), speed 6001000 m/min.

Performance : Lifespan 800-1500 minutes, $R_a\ 0.1\text{-}0.3\ \mu\text{m}$.

Performance : Lifespan 800-1500 minutes, maintenance cost reduced by 20%.

Case : Crankshaft processing, speed 800 m/min, life 1200 minutes, efficiency increased by 30%.

Mould processing :

Materials : Die steel (P20, HRC 3040), stainless steel (316L), 3D printing 316L.

Stainless steel milling :

End mill ($\varnothing\ 12\ \text{mm}$, 4 flutes), WC10%Ni (fine grain, D50 $0.51\ \mu\text{m}$, Cr3C2 0.5 wt %), hardness 18002000 HV, PVD CrN coating ($5\ \mu\text{m}$, hardness 2200 HV, friction 0.2). Helix angle 40° , cutting edge radius 0.03 mm, polished chip flutes ($R_a\ <0.1\ \mu\text{m}$).

Technology

Ball milling for 18 h, pressing at 200 MPa, sintering at 1420°C ($10^{-4}\ \text{Pa}$, 2 h), HIP at 1350°C (120 MPa, 1.5 h), grinding ($R_a\ 0.1\ \mu\text{m}$), PVD CrN (300°C , adhesion $>80\ \text{N}$).

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Cutting data

Speed 1000 m/min, feed 0.08 mm/tooth, depth of cut 0.5 mm, water-based coolant (pH 8, 10 L/min).

Test Data

Life 1000 min (HSS 200 min), Ra 0.25 μm , accuracy ± 0.008 mm, cutting force 300 N (reduced by 25%), wear < 0.04 mm³ / h, no built-up edge.

Selection Recommendations

WCNi (10 wt %) + CrN, $\varnothing$ 12 mm 4- edge milling cutter, helix angle 40°, wet cutting + regular cleaning.

3D Printing 316L Finishing :

Ball end mill ($\varnothing$ 6 mm, 2 flutes), WC8%Co (ultrafine grain, D50 0.20.5 μm , VC 0.5 wt %), hardness 2000-2200 HV, PVD TiAlN+CrN coating (5 μm , hardness 3200 HV, friction 0.2). Ball end radius 3 mm, helix angle 35°, cutting edge radius 0.02 mm, polished groove (Ra < 0.1 μm).

Technology

Ball milling for 20 h, CIP 280 MPa, sintering 1400°C (10^{-5} Pa, 2.5 h), HIP 1350°C (120 MPa, 1.5 h), grinding (Ra 0.1 μm), PVD TiAlN+CrN (350°C, adhesion > 100 N).

Cutting data

Speed 1200 m/min, feed 0.03 mm/tooth, depth of cut 0.2 mm, MQL (0.1 L/h).

Test Data

Life 1200 min (HSS 250 min), Ra 0.15 μm (initial Ra 15 μm), accuracy ± 0.005 mm, cutting force 250 N (reduced by 29%), wear < 0.04 mm³ /h, no clogging.

Selection Recommendations

Ultrafine grain WC+TiAlN+CrN, $\varnothing$ 6 mm 2- flute ball end mill, helix angle 35°, MQL+layered milling.

performance

Lifespan: 1000-2000 minutes, accuracy: ± 0.005 -0.008 mm.

Case

Processing injection mold (316L), speed 1000 m/min, life 1800 minutes, Ra 0.2 μm .

Energy equipment :

Materials : high temperature alloy (GH4169), CFRP.

Knife :

CFRP milling : WC8%Co milling cutter ($\varnothing$ 10 mm, DLC 3 μm), speed 2000 m/min, life 1500 minutes, no delamination.

Performance : Life span 1000-2000 minutes, no delamination/ chipping .

Case : Processing wind turbine blades (CFRP), speed 1500 m/min, life 2000 minutes.

6. Optimization suggestions

Material optimization :

Titanium alloy : ultrafine grain WC (D50 0.20.5 μm), Co 6 wt %, AlTiN 4 μm , heat resistant 1100°C.

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Stainless steel : WCNi (10 wt %), Cr3C2 0.5 wt %, CrN 5 μm , corrosion resistance $<0.01\text{ mm/y}$.

High temperature alloy : medium coarse grain WC (12 μm), Co 12 wt %, TiAlN 4 μm , KIC $>14\text{ MPa}\cdot\text{m}^{1/2}$.

CFRP : ultrafine grain WC (0.20.5 μm), Co 8 wt %, DLC 3 μm , friction <0.08 .

3D printing metal : ultrafine grain WC (0.20.5 μm), Co 8 wt %, TiAlN+CrN 5 μm , accuracy $\pm 0.005\text{ mm}$.

General purpose : Cr3C2/VC 0.5 wt %, hardness increased by 510%.

Process Optimization :

Sintering : HIP 1350°C, 120 MPa, porosity $<0.001\%$, consistency increased by 10%.

Grinding : CNC grinder, diamond grinding wheel (58 μm), cutting edge radius $<5\text{ }\mu\text{m}$, Ra $<0.1\text{ }\mu\text{m}$.

coating :

AlTiN (4 μm , 350°C, bias 100 V), heat resistance increased by 20%.

CrN (5 μm , 300°C, bias 80 V), corrosion resistance increased by 30%.

DLC (3 μm , 300°C, bias 120 V), friction reduction 50%.

3D printing : SLM molding of complex tools (such as internal cooling channels), cycle time reduced by 20%, accuracy of $\pm 0.01\text{ mm}$.

Equipment Optimization :

Sintering furnace: temperature control $\pm 3^\circ\text{C}$, vacuum 10^{-5} Pa .

CNC grinding machine: diamond grinding wheel, deviation $<\pm 0.005\text{ mm}$.

Coating equipment: deposition rate 12 $\mu\text{m/h}$, thickness deviation $<\pm 0.1\text{ }\mu\text{m}$.

Working condition adaptation :

Titanium alloy : dry cutting, AlTiN coating, speed 800-1200 m/min, main deflection angle 75° .

Stainless steel : wet cutting, CrN coating, speed 600-1000 m/min, helix angle 40° .

High temperature alloy : internal cooling (20 bar), TiAlN coating, speed 500800 m/min, top angle 135° .

CFRP : dry cutting, DLC coating, speed 1500-2000 m/min, staggered teeth.

3D printing metal : MQL (0.1 L/h), TiAlN+CrN coating, speed 10001200 m/min, ball end tool.

Testing and verification :

Microstructure : SEM (grain 0.22 μm), EBSD (grain boundary stress $<5\%$).

Performance : ASTM G65 (wear rate $<0.030.05\text{ mm}^3/\text{h}$), high temperature hardness ($>1200\text{ HV}$, 900°C).

Cutting test :

Cutting force: 200550 N (down 2033%).

Lifespan: 8002000 minutes (increased 4.88 times).

Surface: Ra 0.150.3 μm , accuracy $\pm 0.0050.01\text{ mm}$.

Failure: VB $<0.10.2\text{ mm}$, no chipping /delamination.

7. Standards and specifications

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GB/T 183762014 : Porosity <0.01%, uniformity >95%.

GB/T 38502015 : Density 14.515.0 g/cm³ , deviation <±0.1 g/ cm³ .

GB/T 38512015 : Flexural strength 1.82.8 GPa .

GB/T 79972017 : Hardness 14002200 HV, deviation <±50 HV.

ASTM G65 : Wear rate <0.05 mm³ / h.

ISO 6508 : Hardness test, deviation < ±50 HV.

ISO 1832 : Tool geometry, cutting edge deviation <±0.01 mm.

ISO 8688 : Tool life test, cutting time >500 minutes.

8. Conclusion

The cemented carbide high-speed cutting tool achieves high hardness (18002200 HV), wear resistance (wear loss <0.030.05 mm³/h), high temperature red hardness (8001000°C) and cutting stability (life 8002000 minutes) by optimizing materials (ultrafine grain WC 0.20.5 μm , low Co 68 wt%, TiAlN / CrN /DLC coating 35 μm) and advanced manufacturing processes (HIP sintering 1350°C, 120 MPa, PVD coating 300400°C). The tool is suitable for aerospace (titanium alloy, nickel-based alloy, CFRP), automobile (high-strength steel), mold (stainless steel, 3D printing metal) and energy (CFRP) and other fields, with a cutting speed of 5002000 m/min, a processing efficiency increase of 50100%, an accuracy of ±0.0050.01 mm, and Ra 0.150.4 μm . Optimizing ultrafine grains, composite coatings, 3D printing and precision grinding can further reduce costs (100,500 yuan per piece) and improve performance. The challenges lie in the difficulty of processing (diamond grinding costs increase by 20%) and coating adhesion (>80 N required).

CTIA GROUP LTD uses nano WC powder (D50 0.20.5 μm), HIP sintering (porosity <0.001%) and multi-layer PVD coating (TiAlN+CrN , 57 μm) to develop high-performance turning tools, milling cutters and drills to meet the needs of aerospace (lifespan>1500 minutes), automobiles (efficiency increased by 30%) and mold processing (accuracy ±0.005 mm). The products are verified by SEM, ASTM G65 and ISO 1832 to ensure stable performance.

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appendix:

Carbide ball end mills

1. Overview

Carbide ball end mills are milling tools with tungsten-based carbide (such as WC-Co, WC-Ni) as the cutter body or blade material. The cutter head is spherical and suitable for processing complex three-dimensional surfaces, cavities, molds and precision parts. Its high hardness (HV1600-2000), excellent wear resistance and high temperature stability (600-800°C retention strength) make it suitable for processing steel, cast iron, stainless steel, aluminum alloy and high temperature alloy, meeting the needs of aerospace, automotive, mold manufacturing and medical industries for high precision (IT6-IT7) and high quality surface processing.

1. Materials and Manufacturing

Material composition:

It is mainly composed of tungsten carbide (WC, accounting for 80-90%) and binders (such as Co and Ni, accounting for 5-15%), and TiC and TaC are added to improve wear resistance. High Co content (such as WC-10Co) enhances toughness and is suitable for intermittent cutting; Ni-based alloys are corrosion-resistant and suitable for wet processing.

Manufacturing process:

Powder Metallurgy

Mix WC and Co powders (particle size 0.4–1.5 μm), press mold (pressure 300–500 MPa), and vacuum sinter at 1350–1450°C to achieve a hardness of HV1700–1900.

Precision Grinding

The spherical cutter head and spiral groove are processed by diamond grinding wheel, with the edge sharpness <5μm and surface roughness Ra <0.2μm, ensuring cutting accuracy and smooth chip removal.

Coating Technology

Applying PVD coating (such as TiAlN, AlCrN, DLC) with a thickness of 2-4 μm can reduce the friction coefficient to 0.15-0.3 and extend the tool life by 50-100%.

Advantages

Compared with high-speed steel ball end mills, carbide ball end mills have a 2–3 times higher cutting speed (50–200 m/min) and a 3–5 times longer life.

3. Types and Applications

Standard ball end mills

Diameter 2-20mm, 2-4 blades, suitable for mold cavity and curved surface processing, such as automobile lamp mold (precision IT7).

Long neck ball end milling cutter

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High aspect ratio ($L/D > 5$), used for deep cavity processing, such as aviation blade molds (depth 50-100mm).

Micro ball end mills

Diameter 0.1–2 mm, suitable for precision machining, such as medical implants (surface roughness $Ra < 0.2 \mu\text{m}$).

High hardness ball end milling cutter

Machining hardness HRC50-65 materials, suitable for mold steel and high temperature alloys.

Application examples:

Aerospace: Processing titanium alloy turbine blades, cutting speed 80 m/min, tolerance $< 5 \mu\text{m}$.

Automobile industry: Milling plastic mold surfaces, with an annual output of over 5 million pieces and a tool life of 20,000 pieces/ blade .

Medical industry: Processing of orthopedic implants, surface roughness $Ra < 0.1 \mu\text{m}$, precision IT6.

4. Technical features

High efficiency: cutting speed 50–200 m/min, feed rate 0.02–0.2 mm/tooth, processing efficiency increased by 30–50%.

High precision: dimensional tolerance $< 5 \mu\text{m}$, surface roughness $Ra 0.2\text{--}0.4 \mu\text{m}$, meeting ISO 1832 standards.

Durability: Coated ball end mills have a lifespan of 5,000–10,000 pieces, and tool change frequency is reduced by 50%.

Recyclability: Waste tools can be recycled by zinc melting or chemical methods, with a tungsten recovery rate of $> 90\%$ and a cost reduction of 30-40%.

5. Development Trends

Intelligent Optimization

Combined with AI to optimize the tool head radius ($R0.5\text{--}R10$) and cutting path, the machining error is reduced by 25%.

Green Manufacturing

Research and develop low- Co ($< 5\%$) cemented carbide to reduce environmental impact; promote electrochemical recycling technology to reduce waste liquid emissions by 60%.

Advanced coatings

Develop nano-composite coatings (such as TiAlN /DLC) to increase wear resistance by 60% and extend service life by 2 times.

High-performance design

Optimized helix angle ($30\text{--}40^\circ$) and chip grooves reduce cutting forces by 20%, making it suitable for high-speed and dry machining.

Carbide ball end mills have become core tools for complex surfaces and precision machining due to their high hardness, wear resistance and high precision, and are widely used in the aerospace, automotive, mold and medical industries. In the future, through intelligent optimization, green

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recycling and advanced coating technology, carbide ball end mills will further improve processing efficiency, reduce costs and support sustainable development, helping to enhance the competitiveness of China's high-end manufacturing.

appendix:

Carbide end mills

1. Overview

Carbide end mills are vertical milling tools with tungsten-based carbide (such as WC-Co, WC-Ni) as the cutter body or blade material. They have multiple cutting edges and are used to process planes, grooves, steps, cavities and complex curved surfaces. Their high hardness (HV1600-2000), excellent wear resistance and high temperature stability (600-800°C retention strength) make them suitable for processing steel, cast iron, stainless steel, aluminum alloy and high-temperature alloys, meeting the needs of aerospace, automotive, mold manufacturing and precision machinery industries for high precision (IT6-IT8) and high-efficiency processing.

2. Materials and manufacturing

Material composition

It is mainly composed of tungsten carbide (WC, accounting for 80-90%) and binders (such as Co and Ni, accounting for 5-15%), and TiC and TaC are added to improve wear resistance. High Co content (such as WC-10Co) increases toughness and is suitable for intermittent cutting; Ni-based alloys are corrosion-resistant and suitable for wet processing.

Manufacturing process

Powder metallurgy: Mix WC and Co powders (particle size 0.5–2μm), press molding (pressure 300–500 MPa), vacuum sintering at 1350–1450°C, and the hardness reaches HV1700–1900.

Precision grinding: Diamond grinding wheel is used to process the blade and spiral groove, with edge sharpness <5μm and surface roughness Ra <0.2μm, ensuring smooth chip discharge.

Coating technology: Apply PVD or CVD coating (such as TiAlN, AlCrN, TiSiN) with a thickness of 2-5μm, reduce the friction coefficient to 0.2-0.3, and extend the tool life by 50-100%.

Advantages: Carbide end mills cut 2–4 times faster (50–250 m/min) and last 3–5 times longer than HSS end mills.

3. Types and Applications

Carbide flat end mills

For plane and groove processing, suitable for automotive mold cavities (depth 10-50mm, accuracy IT7).

Carbide Round Nose End Mills

The arc blade is suitable for curved surface and contour processing and is used in aviation turbine blades with an accuracy of IT6.

Carbide Ball Nose End Mills

Processing of complex 3D surfaces, such as medical implant molds, with surface roughness Ra<0.4μm.

Carbide roughing end mills

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The large helix angle (35–45°) and wave-shaped edge are suitable for efficient material removal, such as aluminum alloy fuselage parts.

Application examples:

Automobile industry: Processing gearbox housing grooves, with an annual output of over 10 million pieces and a tool life of 50,000 pieces/ blade .

Aerospace: Milling titanium alloy casing, cutting speed 100 m/min, tolerance <8μm.

Mold manufacturing: Processing high-hardness mold steel (HRC50-60) can increase tool life by 40%.

2. Technical features

High efficiency: cutting speed 50–250 m/min, feed rate 0.05–0.3 mm/tooth, machining efficiency increased by 40–60%.

High precision: dimensional tolerance <8μm, surface roughness Ra0.4–0.8μm, meeting ISO 1832 standards.

Durability: Coated end mills have a lifespan of 5,000–15,000 pieces, and tool change frequency is reduced by 50%.

Recyclability: Waste tools can be recycled by zinc melting or chemical methods, with a tungsten recovery rate of >90% and a cost reduction of 30-40%.

5. Development Trends

Intelligent optimization: Combined with AI to optimize the number of edges (2-6 edges) and cutting parameters, the machining error is reduced by 30%.

Green Manufacturing: Research and develop low- Co (<5%) cemented carbide to reduce environmental impact; promote ionic liquid recycling technology to reduce waste liquid emissions by 60%.

Advanced coatings: Develop nanocomposite coatings (such as TiAlN /DLC) that increase wear resistance by 60% and extend service life by 2 times.

High-performance design: Optimized helix angle (30–45°) and chip grooves reduce cutting forces by 20%, suitable for high-speed machining.

Carbide end mills have become the core tools for milling due to their high hardness, wear resistance and high precision, and are widely used in the aerospace, automotive and mold manufacturing industries. In the future, through intelligent optimization, green recycling and advanced coating technology, carbide end mills will further improve processing efficiency, reduce costs and support sustainable development, helping to enhance the competitiveness of China's high-end manufacturing.

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appendix:

Carbide multi-tooth milling cutter

1. Carbide multi-tooth milling cutter

Carbide multi-tooth milling cutters are cutting tools with tungsten-based carbide (such as WC-Co, WC-Ni) as the cutter body or blade material, with multiple cutting teeth, and are widely used in the milling of planes, grooves, steps, curved surfaces and complex surfaces. Its high hardness (HV1600-2000), excellent wear resistance and high temperature stability (600-800°C strength retention) make it suitable for processing steel, cast iron, stainless steel, aluminum alloy and high-temperature alloys, meeting the needs of aerospace, automotive, mold manufacturing and energy industries for high-precision (IT6-IT8) and high-efficiency processing.

2. Materials and manufacturing of cemented carbide multi-tooth milling cutters

Material composition: Mainly composed of tungsten carbide (WC, accounting for 80-90%) and binder (such as Co, Ni, accounting for 5-15%), with TiC and TaC added to enhance wear resistance. High Co content (such as WC-10Co) improves toughness and is suitable for intermittent milling; Ni-based alloys are corrosion-resistant and suitable for wet machining.

Manufacturing process:

Powder metallurgy: Mix WC and Co powders (particle size 0.5–2μm), press molding (pressure 300–500 MPa), vacuum sintering at 1350–1450°C, and the hardness reaches HV1700–1900.

Precision grinding: CBN or diamond grinding wheel is used to process the teeth and grooves, with edge sharpness <5μm and surface roughness Ra <0.2μm, ensuring smooth chip discharge.

Coating technology: Apply PVD or CVD coating (such as TiAlN, AlCrN, TiSiN) with a thickness of 2-5μm, reduce the friction coefficient to 0.2-0.3, and extend the tool life by 50-100%.

Advantages: Compared with high-speed steel milling cutters, carbide multi-tooth milling cutters have a cutting speed 2-4 times higher (50-250 m/min) and a lifespan 3-5 times longer.

3. Types and applications of carbide multi-tooth milling cutters

Carbide Multi-tooth End Mills

Multi-tooth design (4-8 teeth) is suitable for side and groove processing, such as automotive mold cavities (depth 10-50mm, accuracy IT7).

Carbide multi-tooth face milling cutter

Large diameter and multiple teeth (6-12 teeth) for efficient flat surface processing, suitable for aviation aluminum alloy wing panels (surface roughness Ra<0.8μm).

Carbide multi-tooth round nose milling cutter

The arc blade is suitable for curved surface processing and is used in turbine blades with an accuracy of IT6.

Carbide multi-tooth keyway milling cutter

Processing high-precision keyways, such as wind turbine main shafts (slot width 5–20mm, tolerance <10μm).

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Application examples:

Automobile industry: Processing of engine cylinder head planes, with an annual output of over 20 million pieces and a tool life of 50,000 pieces/ blade .

Aerospace: Milling titanium alloy casing, cutting speed 100 m/min, surface roughness $Ra < 0.4\mu m$.

Mold manufacturing: Processing high-hardness mold steel (HRC50-60) can increase tool life by 40%.

4. Technical features of carbide multi-tooth milling cutter

High efficiency: cutting speed 50–250 m/min, feed rate 0.05–0.3 mm/tooth, machining efficiency increased by 40–60%.

High precision: dimensional tolerance $< 8\mu m$, surface roughness $Ra 0.4–0.8\mu m$, meeting ISO 1832 standards.

Durability: The life of coated milling cutters is 5,000–15,000 pieces, and the frequency of tool changes is reduced by 50%.

Recyclability: Waste tools can be recycled by zinc melting or chemical methods, with a tungsten recovery rate of $> 90\%$ and a cost reduction of 30-40%.

5. Development trend of cemented carbide multi-tooth milling cutters

Intelligent Optimization

Combined with AI optimization of the number of teeth (4-12 teeth) and cutting parameters, the machining error is reduced by 30%.

Green Manufacturing

Develop low- Co ($< 5\%$) cemented carbide to reduce environmental impact; promote ionic liquid recycling technology to reduce waste liquid emissions by 60%.

Advanced coatings

Develop nano-composite coatings (such as $TiAlN/Si_3N_4$) to increase wear resistance by 60% and extend service life by 2 times.

Modular design

Promote the standardization of indexable inserts and cutter heads (ISO 1832), reducing inventory costs by 20%.

Carbide multi-tooth milling cutters have become the core tools for milling processing due to their high hardness, wear resistance and high precision, and are widely used in the aerospace, automotive and mold manufacturing industries. In the future, through intelligent optimization, green recycling and advanced coating technology, carbide multi-tooth milling cutters will further improve processing efficiency, reduce costs and support sustainable development, helping to enhance the competitiveness of China's high-end manufacturing.

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CTIA GROUP LTD

30 Years of Cemented Carbide Customization Experts

Core Advantages

30 years of experience: We are well versed in cemented carbide production and processing , with mature and stable technology and continuous improvement .

Precision customization: Supports special performance and complex design , and focuses on customer + AI collaborative design .

Quality cost: Optimized molds and processing, excellent cost performance; leading equipment, RMI, ISO 9001 certification.

Serving Customers

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appendix:

Carbide solid drill

1. Overview of Carbide Solid Drill

Solid carbide drills are drilling tools made of tungsten-based carbide (such as WC-Co, WC-Ni) as the main material, and are widely used in hole processing, such as drilling, reaming and reaming. Its high hardness (HV1600-2000), excellent wear resistance and high temperature stability (600-800°C still maintains strength) make it suitable for processing steel, cast iron, stainless steel, aluminum alloy and high-temperature alloys, meeting the needs of aerospace, automotive, mold manufacturing and energy industries for high-precision (IT7-IT9) and high-efficiency hole processing.

2. Materials and manufacturing of cemented carbide drill bits

Material composition

It is mainly composed of tungsten carbide (WC, accounting for 85-95%) and binder (such as Co, accounting for 5-12%), and TiC and VC are added to improve wear resistance. High Co content (such as WC-10Co) improves toughness and is suitable for intermittent cutting; low Co content (such as WC-6Co) enhances hardness and is suitable for high-speed processing.

Manufacturing process

Powder metallurgy: Mix WC and Co powders (particle size 0.4–1.5μm), press molding (pressure 300–500 MPa), vacuum sintering at 1350–1450°C, and the hardness reaches HV1800–2000.

Precision grinding: Diamond grinding wheel is used to process the drill bit edge and spiral groove, the edge sharpness is <5μm, and the surface roughness Ra is <0.2μm, ensuring smooth chip discharge.

Coating technology: Application of PVD coating (such as TiAlN, AlCrN) with a thickness of 2–4μm, reduces the friction coefficient to 0.2-0.3 and improves wear resistance by 50-80%.

Advantages

Compared with high-speed steel drills, carbide solid drills have a cutting speed 2–3 times higher (30–150 m/min) and a lifespan 4–6 times longer.

3. Types and applications of carbide solid drill bits

Carbide Solid Twist Drill

Standard spiral design, suitable for general hole processing, such as automobile engine cylinder block holes (diameter 5-50mm, accuracy IT8).

Carbide solid center drill

Used for positioning and pre-drilling, processing center holes of aviation parts, accuracy IT7.

Carbide solid deep hole drill

High aspect ratio ($L/D > 5$), with internal cooling channel, processing deep holes of hydraulic valve bodies (depth 100-500mm).

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Carbide integral step drill

Complete multi-level hole processing at one time, suitable for mold parts, and increase efficiency by 30%.

Application cases of cemented carbide integral drill :

Automobile industry: Processing gearbox housing holes, with an annual output of over 100 million pieces and a drill life of 20,000 holes/ blade .

Aerospace: Drilling titanium alloy casing holes, cutting speed 60 m/min, hole diameter tolerance <10 μ m.

Energy industry: Processing wind turbine spindle holes, surface roughness Ra < 0.8 μ m, life increased by 50%.

4. Technical features of carbide integral drill bits

High efficiency: cutting speed 30–150 m/min, feed rate 0.05–0.3 mm/rev, machining efficiency increased by 40%.

High precision: aperture tolerance <8 μ m, roundness error <5 μ m, meeting ISO 8015 standards.

Durability: Coated drill bits have a lifespan of 10,000–20,000 holes, and tool change frequency is reduced by 60%.

Recyclability: Used drill bits can be recycled through zinc melting or chemical methods, with a tungsten recovery rate of >90% and a cost reduction of 30–40%.

5. Development trend of cemented carbide integral drill

Intelligent design: Combined with AI to optimize the helix angle (25–35°) and cutting parameters, the machining error is reduced by 25%.

Green manufacturing: Research and develop low- Co (<5%) cemented carbide to reduce environmental impact; promote electrochemical recycling technology to reduce waste liquid emissions by 60%.

Advanced coatings: Develop nano-multilayer coatings (such as TiAlN /DLC), which improve wear resistance by 60% and extend service life by 2 times.

Internal coolant technology: Optimized internal coolant channel design (pressure 10-20 bar), cutting temperature reduced by 30%, suitable for dry or minimal lubrication processing.

hole processing due to their high hardness, wear resistance and high precision, and are widely used in the aerospace, automotive and energy industries. In the future, through intelligent design, green recycling and advanced coating technology, solid carbide drills will further improve processing efficiency, reduce costs and support sustainable development, helping to enhance the competitiveness of China's high-end manufacturing.

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appendix:

Carbide external turning tool

1. Overview of Carbide External Turning Tools

Carbide external turning tools are cutting tools with tungsten-based carbide (such as WC-Co, WC-Ni) as the tool head material, and are widely used for turning external cylindrical surfaces, end faces, steps and grooves. Its high hardness (HV1600-2000), excellent wear resistance and high temperature stability (600-800°C strength retention) make it suitable for machining carbon steel, alloy steel, stainless steel, cast iron and high temperature alloys, meeting the needs of the automotive, aerospace, mold manufacturing and general machinery industries for high precision (IT6-IT8) and high efficiency machining.

2. Materials and manufacturing of cemented carbide external turning tools

Material composition: Mainly composed of tungsten carbide (WC, accounting for 80-90%) and binder (such as Co, Ni, accounting for 5-15%), adding TiC and TaC to enhance wear resistance. Co improves toughness (such as WC-8Co for rough machining), and Ni improves corrosion resistance (suitable for wet cutting).

Manufacturing process:

Powder metallurgy: Mix WC and Co powders (particle size 0.5–2μm), press molding (pressure 200–400 MPa), vacuum sintering at 1350–1450°C, and the hardness reaches HV1700–1900.

Precision grinding: Diamond grinding wheel is used to process the cutter head, with edge sharpness <5μm and surface roughness Ra <0.2μm, ensuring cutting accuracy.

Coating technology: Apply PVD or CVD coating (such as TiN, TiCN, Al₂O₃) with a thickness of 2–6μm, reduce the friction coefficient to 0.2-0.3, and extend the tool life by 50-80%.

Advantages: Compared with high-speed steel turning tools, carbide turning tools have a cutting speed 2-4 times higher (50-200 m/min) and a lifespan 3-6 times longer.

3. Types and applications of cemented carbide external turning tools

Carbide external turning tool - indexable turning tool

The blades are replaceable and highly versatile, making them suitable for mass production, such as machining automobile crankshafts (diameter 50-200mm, precision IT7).

Carbide external turning tool - welded turning tool

The cutter head is welded to the steel cutter body, which is low in cost and suitable for small and medium-sized processing plants to process the outer circle of the pump body.

Carbide external turning tool - integral turning tool

The cutter head is integrated with the cutter body, which is suitable for high-precision processing, such as aviation turbine shafts (diameter 20-100mm, precision IT6).

Application examples:

Automobile industry: Processing engine cylinders, with an annual output of over 50 million pieces

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and a tool life of 10,000 pieces/ blade .

Aerospace: Turning titanium alloy turbine disk, cutting speed 80 m/min, surface roughness $Ra < 0.8\mu m$.

Mold manufacturing: Processing high-hardness mold steel (HRC50-60) can increase tool life by 40%.

4. Technical characteristics of cemented carbide external turning tools

High efficiency: cutting speed 50–200 m/min, feed rate 0.1–0.4 mm/rev, machining efficiency increased by 30–50%.

High precision: dimensional tolerance $< 10\mu m$, surface roughness $Ra 0.4–0.8\mu m$, meeting ISO 1832 standards.

Durability: The life of coated turning tools reaches 5,000-10,000 pieces, and the tool change frequency is reduced by 60%.

Recyclability: Waste blades can be recycled by zinc melting or chemical methods, with a tungsten recovery rate of $> 90\%$ and a cost reduction of 30–40%.

5. Development trend of cemented carbide external turning tools

Intelligent optimization: Combined with AI to optimize cutting parameters (such as main deflection angle and cutting depth), processing efficiency is improved by 20%.

Green Manufacturing: Research and develop low- Co ($< 5\%$) cemented carbide to reduce environmental impact; promote electrochemical recycling technology to reduce waste liquid emissions by 50%.

Advanced coatings: Develop nanocomposite coatings (such as $TiAlN / Si_3N_4$) that increase wear resistance by 60% and extend service life by 2 times.

Modular design: Promote the standardization of indexable inserts (ISO 1832), reducing tool inventory costs by 25%.

With its high hardness, wear resistance and high precision, cemented carbide external turning tools have become the core tools for external turning, and are widely used in the automotive, aerospace and mold manufacturing industries. In the future, through intelligent optimization, green recycling and advanced coating technology, cemented carbide external turning tools will further improve processing efficiency, reduce costs and support sustainable development, helping to enhance the competitiveness of China's high-end manufacturing.

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appendix:

Carbide Gear Cutters

1. Overview of Carbide Gear Tools

Carbide gear cutters are special cutting tools made of tungsten-based carbide (such as WC-Co, WC-Ni) as the main material, and are widely used in gear processing, such as gear hobbing, gear shaping, gear shaving and gear grinding. Its high hardness (HV1600-2000), excellent wear resistance and high temperature red hardness (600-800°C still maintains high strength) make it suitable for processing materials such as high-strength steel, alloy steel and stainless steel, meeting the needs of the automotive, aerospace, energy and heavy machinery industries for high-precision gears (accuracy up to ISO 4-6).

2. Carbide gear tool materials and manufacturing

Material composition: Mainly composed of tungsten carbide (WC, accounting for 80-90%) and binder (such as Co, Ni, accounting for 5-15%), with a small amount of TiC and TaC added to improve wear resistance. The higher the Co content, the better the toughness (such as WC-10Co); Ni-based alloys are corrosion-resistant and suitable for special environments.

Manufacturing process:

Powder metallurgy: Mix WC, Co and other powders (particle size 0.5-2 μ m), press into shape (pressure 300-500 MPa), and sinter at 1350-1500°C in vacuum or hydrogen atmosphere to achieve a hardness of HV1800.

Precision grinding: CBN grinding wheel is used to process the tool tooth profile, with surface roughness $R_a < 0.2\mu$ m and cutting edge radius $< 10\mu$ m to ensure cutting accuracy.

Coating technology: Apply PVD or CVD coating (such as TiN, TiAlN, AlCrN) with a thickness of 2-5 μ m, reduce the friction coefficient (0.2-0.4), and extend the service life by 50-100%.

Advantages: Compared with high-speed steel (HSS), carbide tool life is 3-5 times longer and cutting speed is 2-3 times higher (100-300 m/min).

3. Types and applications of cemented carbide gear cutters

Carbide Gear Hobbing Cutter

Used for roughing and finishing spur and helical gears with high processing efficiency, suitable for automotive transmission gears (module 1-10).

Carbide gear shaping cutter

Processing of internal gears and special tooth shapes with ISO 5 accuracy for aviation gearboxes.

Carbide Gear Shaving Cutter

The tooth surface is finely machined, with a surface roughness of $R_a < 0.8\mu$ m, which is suitable for mass production of high-precision gears.

Carbide Gear Grinding Knife

The hardened tooth surface (HRC > 60) is machined using cemented carbide substrate combined with

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CBN coating, with an accuracy of ISO 3-4, for wind power and high-speed rail gears.

Application examples:

Automobile industry: Processing of gearbox gears, with an annual output of over 100 million pieces and a tool life of 100,000 pieces/ blade .

Aerospace: Machining turbine engine gears, module 0.5–2, ISO 4 accuracy, 20% reduction in cutting forces.

4. Technical characteristics of carbide gears

High efficiency: cutting speed 150-300 m/min, feed rate 0.1-0.5 mm/rev, machining efficiency increased by 40%.

High precision: tooth profile error $<5\mu\text{m}$, tooth pitch error $<3\mu\text{m}$, meeting DIN 3962 standard.

Durability: Coated carbide tool life reaches 5,000-10,000 pieces, reducing tool change frequency by 50%.

Recyclability: Waste tools can be recycled by chemical method or zinc melting method , with tungsten recovery rate $>90\%$ and cost reduction of 30-40%.

5. Development trend of cemented carbide gears

Intelligent design: Combined with AI to optimize tooth shape and cutting parameters, the processing error is reduced by 30%.

Green Manufacturing: Develop low-Co ($<5\%$) or Co-free cemented carbide to reduce environmental impact; promote ionic liquid recycling technology to reduce waste liquid emissions by 60%.

Composite coating: Research and development of nano multilayer coatings (such as TiAlN /DLC), which improves wear resistance by 50% and extends service life by 2 times.

Additive Manufacturing : Explore 3D printed carbide tool substrates to reduce the manufacturing cost of complex tooth shapes by 20%.

Carbide gear cutting tools have become the core tools for gear processing due to their high hardness, wear resistance and high precision, and are widely used in the automotive, aerospace and energy industries. In the future, through intelligent design, green recycling and advanced coating technology, carbide gear cutting tools will further improve efficiency, reduce costs and support sustainable development, helping to enhance the global competitiveness of China's high-end manufacturing.

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appendix:

Carbide wind turbine gear cutter

The carbide wind turbine gear cutter is based on tungsten carbide (WC)-based carbide (WC 8594 wt %, Co 615 wt %). Through precision grinding and PVD/CVD coating (such as TiAlN , AlCrN , 46 μm), it achieves high hardness (18002200 HV), wear resistance (wear loss $<0.05 \text{ mm}^3 / \text{h}$, ASTM G65) and high temperature red hardness (8001000°C, hardness $>1200 \text{ HV}$). It is specially designed for wind turbine gears (42CrMo4, 18CrNiMo76, HRC 5562, module 1040), suitable for gear hobbing, gear shaping, disc milling and hard turning, with a cutting speed of 100500 m/min, a life of 5002000 minutes, a tooth profile accuracy of AGMA 1012, and a surface roughness of Ra 0.40.8 μm .

This article is based on national standards (GB/T 183762014, GB/T 79972017) and industry practices, and explains cutting tools, manufacturing processes, performance, applications and optimization directions. It moderately recommends the high-performance cutting tool customization capabilities of CTIA GROUP LTD and has nothing to do with new energy electrolytic cells and carburizing/decarburization processes.

1. Overview of Carbide Wind Power Gear Tools

1.1 Definition and characteristics of cemented carbide wind turbine gear tools

The cemented carbide wind turbine gear cutters meet the processing requirements of large modulus (1040) and high hardness (HRC 5562) of wind turbine gears through ultrafine/ medium-coarse grain WC (0.22 μm) substrate, PVD/CVD coating (TiAlN / AlCrN) and precision machining (tooth profile deviation $<\pm 0.005 \text{ mm}$).

Features of carbide wind power gear cutters :

High hardness : 18002200 HV, **wear resistance is 510** times better than high-speed steel (HSS, 800 HV) .

Heat resistance : 8001000°C, suitable for dry/minimum quantity lubrication (MQL) cutting.

Wear resistance : wear rate $<0.05 \text{ mm}^3 / \text{h}$, life span 500-2000 minutes.

Impact resistance : flexural strength 1.82.8 GPa , fracture toughness KIC 1015 $\text{MPa} \cdot \text{m}^{1/2}$.

Applications : Wind power gears (planetary gears, main shaft gears), gearbox components.

1.2 Types of Carbide Wind Turbine Gear Cutters

Hob : Coarse/fine gear hobbing, speed 100400 m/min.

Gear shaping cutter : internal/external gear processing, speed 150300 m/min.

Disc milling cutter : tooth groove milling, speed 200500 m/min.

Hard turning tool : hard turning (HRC 5562), speed 80200 m/min.

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1.3 Advantages of Carbide Wind Power Gear Tools

Efficiency : Cutting speed is 35 times higher than HSS , and efficiency is increased by 3050%.

Life : Coated tool life 500-2000 minutes (HSS 100-300 minutes).

Precision : Tooth profile accuracy AGMA 1012, Ra 0.40.8 μm .

Adaptability : Suitable for large modulus, hard machining , dry/wet cutting.

2. Cemented Carbide Wind Power Gear Tool Materials

2.1 Ingredients

Carbide wind turbine gear tool base :

WC : 8594 wt %, grain size 0.22 μm .

Ultrafine grain (0.2-0.5 μm): hardness 2000-2200 HV, fine machining.

Medium coarse grain (12 μm): toughness KIC 1215 $\text{MPa}\cdot\text{m}^{1/2}$, rough machining.

Co : 615 wt %.

Low Co (68 wt %): hardness 18002200 HV, strong wear resistance.

High Co (1015 wt %): flexural strength 2.22.8 GPa , good impact resistance.

Additive : Cr3C2/VC (0.21 wt %), hardness increased by 510%.

Carbide wind turbine gear tool coating :

TiAlN (PVD) : hardness 3000-3300 HV, heat resistance 900-1100°C, lifespan increased by 3050%.

AlCrN (PVD) : Hardness 3000 HV, friction coefficient 0.3, suitable for hard machining .

GC4240 (CVD) : Hardness 2800 HV, excellent wear resistance, suitable for rough machining.

2.2 Gradient structure of cemented carbide wind turbine gear cutter

Surface : low Co (68 wt %), ultrafine grain WC (0.2-0.5 μm), hardness 2000-2200 HV.

Core : High Co (1012 wt %), medium-coarse grain WC (12 μm), KIC 1215 $\text{MPa}\cdot\text{m}^{1/2}$.

Advantages : Wear resistance increased by 2030%, impact resistance increased by 1520%, crack probability reduced by 20%.

Preparation : Layered pressing + HIP sintering (1350°C, 120 MPa).

2.3 Performance requirements of cemented carbide wind turbine gear tools

Hardness: 18002200 HV (GB/T 79972017).

Flexural strength: 1.82.8 GPa (GB/T 38512015).

Fracture toughness: 1015 $\text{MPa}\cdot\text{m}^{1/2}$.

Wear resistance: Wear rate $<0.05 \text{ mm}^3 / \text{h}$ (ASTM G65).

Thermal conductivity: 80100 W/ $\text{m}\cdot\text{K}$.

3. Manufacturing process of cemented carbide wind turbine gear cutters

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3.1 Powder preparation

Raw materials : WC (D50 0.22 μm , purity >99.9%), Co (D50 12 μm), Cr₃C₂/VC (D50 0.51 μm).

Ball milling : planetary ball mill (ZrO₂ balls, 10:1), 300 rpm, 1624 h, particle size deviation $\leq \pm 0.1 \mu\text{m}$, uniformity >95%.

3.2 Forming

Method : Cold isostatic pressing (CIP).

Parameters : 250300 MPa, holding pressure 60 seconds, steel mold (deviation $\leq \pm 0.05 \text{ mm}$), billet density 8.710.5 g/cm³ .

Results : Dimensional deviation $\leq \pm 0.1 \text{ mm}$, crack rate <1%.

3.3 Sintering

Method : Vacuum sintering + HIP.

parameter :

Dewaxing: 200600°C, 3°C/min, H₂ atmosphere (O₂ <5 ppm), 10^{-2} Pa .

Sintering: 13501450°C, $10^{-4} 10^{-5} \text{ Pa}$, 23 h.

HIP: 1350°C, 120 MPa (Ar), 12 h.

Results : Density 14.815.0 g/cm³ , porosity <0.001%, hardness 18002200 HV.

3.4 Precision Machining

Grinding : CNC grinder, diamond wheel (510 μm), 3000 rpm, feed 0.010.05 mm/pass, tooth profile deviation $\leq \pm 0.005 \text{ mm}$, Ra 0.10.2 μm .

Polishing : diamond polishing paste (13 μm), 800 rpm, Ra <0.1 μm .

3.5 Coating

Method : PVD/CVD (Ti/Al/Cr targets, >99.99%).

Parameters : TiAlN / AlCrN (46 μm), 10^{-4} Pa , 300-450°C, bias 80 to 100 V, deposition rate 1 μm /h.

Results : Adhesion >80 N, heat resistance 9001100°C, life increased by 3050%.

3.6 Detection

Microstructure : SEM (grain 0.22 μm), XPS (deviation $\leq \pm 0.1 \text{ wt } \%$).

Performance : Hardness deviation $\leq \pm 50 \text{ HV}$ (ISO 6508), wear volume <0.05 mm³ / h (ASTM G65), flexural strength 1.82.8 GPa .

Geometry : CMM, tooth form deviation $< \pm 0.005 \text{ mm}$ (AGMA 1012).

4. Application scenarios of cemented carbide wind turbine gear tools

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Carbide wind turbine gear cutting tools provide cutting tools, process parameters, test data and selection suggestions for the following working conditions for efficient machining of wind turbine gears (module 1040, HRC 5562):

Rough gear hobbing (42CrMo4, HRC 55) :

Working conditions : material 42CrMo4 (HRC 55), module 20, gear diameter Ø 800 mm, rough machining.

Knife :

Type : Hob (Ø 200 mm, 12 teeth).

Matrix : WC12%Co (medium-coarse grain, D50 12 µm , VC 0.5 wt %), hardness 16001800 HV, KIC 1415 MPa·m^{1/2}.

Coating : CVD GC4240 (6 µm , hardness 2800 HV, heat resistance 1000°C).

Geometry : pressure angle 20°, tooth top radius 0.5 mm, tooth flanks polished (Ra <0.1 µm).

Process : ball milling for 22 hours, CIP 300 MPa, sintering 1450°C (10⁻⁵ Pa, 3 hours), HIP 1350°C (120 MPa, 2 hours), grinding (tooth profile deviation <±0.005 mm), CVD GC4240 (450°C, adhesion >80 N).

Cutting parameters : speed 200 m/min, feed 2 mm/r, depth of cut 5 mm, MQL (0.2 L/h).

Test data :

Lifespan: 800 minutes (HSS 200 minutes, 4 times longer).

Accuracy: AGMA grade 10, Ra 0.8 µm .

Cutting force: 1200 N (HSS 1500 N, reduced by 20%).

Wear loss: VB <0.3 mm, <0.05 mm³ / h.

Selection recommendation : medium-coarse grain WC + high Co (12 wt %) + GC4240, Ø 200 mm hob, MQL + regular inspection of tooth surface wear.

Precision gear hobbing (18CrNiMo76, HRC 60) :

Working conditions : material 18CrNiMo76 (HRC 60), module 15, gear diameter Ø 600 mm, fine machining.

Knife :

Type : Hob (Ø 180 mm, 10 teeth).

Matrix : WC6%Co (ultrafine grain, D50 0.20.5 µm , Cr3C2 0.5 wt %), hardness 20002200 HV.

Coating : PVD TiAlN (4 µm , hardness 3300 HV, heat resistance 1100°C).

Geometry : pressure angle 20°, tooth tip radius 0.3 mm, cutting edge radius 0.02 mm.

Process : ball milling for 20 hours, CIP 280 MPa, sintering 1400°C (10⁻⁵ Pa, 2.5 hours), HIP 1350°C (120 MPa, 1.5 hours), grinding (Ra 0.1 µm), PVD TiAlN (350°C, adhesion >100 N).

Cutting parameters : speed 300 m/min, feed 0.5 mm/r, cutting depth 1 mm, dry cutting.

Test data :

Lifespan: 1200 minutes (HSS 250 minutes, 4.8 times longer).

Accuracy: AGMA grade 12, Ra 0.4 µm .

Cutting force: 800 N (HSS 1000 N, reduced by 20%).

Wear loss: VB <0.2 mm, <0.04 mm³ / h.

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Selection recommendation : ultrafine grain WC + low Co (6 wt %) + TiAlN , Ø 180 mm hob, dry cutting + high-precision machine tool.

Gear shaping (42CrMo4, HRC 58) :

Working conditions : Material 42CrMo4 (HRC 58), module 25, internal gear Ø 1000 mm.

Knife :

Type : Gear shaping cutter (Ø 150 mm, 8 teeth).

Matrix : WC10%Co (fine grain, D50 0.51 µm , Cr3C2 0.5 wt %), hardness 18002000 HV.

Coating : PVD AlCrN (5 µm , hardness 3000 HV, friction 0.3).

Geometry : pressure angle 20°, cutting edge radius 0.03 mm, tooth side polished (Ra <0.1 µm).

Processing : ball milling for 18 hours, CIP 280 MPa, sintering 1420°C (10⁻⁴ Pa, 2 hours), HIP 1350°C (120 MPa, 1.5 hours), grinding (Ra 0.1 µm), PVD AlCrN (400°C, adhesion >80 N).

Cutting parameters : speed 200 m/min, feed 0.1 mm/stroke, depth of cut 2 mm, wet cutting (10 L/min).

Test data :

Lifespan: 1000 minutes (HSS 300 minutes, increased 3.3 times).

Accuracy: AGMA grade 11, Ra 0.6 µm .

Cutting force: 1000 N (HSS 1300 N, 23% reduction).

Wear loss: VB <0.25 mm, <0.05 mm³ / h.

Selection suggestion : fine grain WC+AlCrN , Ø 150 mm gear shaping cutter, wet cutting + low vibration machine tool.

Hard turning (18CrNiMo76, HRC 62) :

Working conditions : material 18CrNiMo76 (HRC 62), module 15, gear diameter Ø 500 mm, fine machining.

Knife :

Type : Hard turning tool (indexable insert, CNMG120408).

Matrix : WC6%Co (ultrafine grain, D50 0.20.5 µm , Cr3C2 0.5 wt %), hardness 20002200 HV.

Coating : PVD TiAlN (4 µm , hardness 3300 HV, heat resistance 1100°C).

Geometry : Main rake angle 75°, cutting edge inclination angle 6°, cutting edge radius 0.02 mm, 3D chip breaker .

Process : ball milling for 20 hours, CIP 280 MPa, sintering 1400°C (10⁻⁵ Pa, 2.5 hours), HIP 1350°C (120 MPa, 1.5 hours), grinding (edge radius <5 µm), PVD TiAlN (350°C, adhesion >100 N).

Cutting parameters : speed 150 m/min, feed 0.1 mm/r, cutting depth 0.5 mm, dry cutting.

Test data :

Lifespan: 1500 minutes (HSS 200 minutes, increased 7.5 times).

Accuracy: AGMA grade 12, Ra 0.4 µm , ±0.01 mm.

Cutting force: 600 N (HSS 800 N, reduced by 25%).

Wear loss: VB <0.15 mm, <0.04 mm³ / h.

Selection recommendations : ultrafine grain WC+TiAlN , CNMG120408MF, dry cutting+high rigidity machine tools.

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5. Performance analysis of cemented carbide wind turbine gear tools

parameter	Carbide Tools	High Speed Steel (HSS)
Hardness (HV)	18002200	800900
Flexural Strength (GPa)	1.82.8	34
Toughness (KIC)	1015 MPa·m ^{1/2}	2050 MPa·m ^{1/2}
Wear resistance (mm ³ / h)	<0.05	0.20.5
Heat resistance (°C)	8001000	500600
Cutting speed (m/min)	100500	20100
Lifespan (minutes)	5002000	100300
Ra (μm)	0.40.8	1.02.0

Highlights :

Wear resistance: Ultrafine grain WC+TiAlN / AlCrN , wear <0.05 mm³ / h, service life increased by 37.5 times .

Heat resistance: 8001000°C, hardness>1200 HV, dry cutting.

Efficiency: Speed 100500 m/min, efficiency increased by 3050%.

Accuracy: AGMA 1012 grade, Ra 0.40.8 μm .

6. Optimization suggestions for carbide wind turbine gear tools

Material optimization :

Rough machining : medium-coarse grain WC (12 μm), Co 12 wt %, GC4240 (6 μm), wear resistance increased by 20%.

Finishing : ultrafine grain WC (0.20.5 μm), Co 6 wt %, TiAlN (4 μm), accuracy ±0.01 mm.

Gear shaping : fine-grained WC (0.51 μm), AlCrN (5 μm), impact resistance increased by 15%.

Additive : Cr3C2/VC 0.5 wt %, hardness increased by 510%.

Process Optimization :

Sintering : HIP 1350°C, 120 MPa, porosity <0.001%, wear resistance increased by 15%.

Grinding : CNC grinding machine, diamond grinding wheel (58 μm), tooth profile deviation <±0.005 mm, Ra <0.1 μm .

coating :

TiAlN (4 μm , 350°C, bias 100 V), heat resistance increased by 20%.

AlCrN (5 μm , 400°C, bias 80 V), shock resistance increased by 15%.

GC4240 (6 μm , 450°C), wear resistance increased by 25%.

3D printing : SLM molding of complex tooth shapes, cycle time reduced by 20%, accuracy of ±0.01 mm.

Equipment Optimization :

Sintering furnace: temperature control ±3°C, 10⁻⁵ Pa.

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CNC grinding machine: tooth profile deviation $\leq \pm 0.005$ mm.

Coating equipment: deposition rate $12 \mu\text{m/h}$, deviation $\leq \pm 0.1 \mu\text{m}$.

Working condition adaptation :

Rough gear hobbing : medium-coarse grain WC+GC4240, speed 200300 m/min, MQL.

Precision gear hobbing : ultrafine grain WC+TiAlN, speed 250400 m/min, dry cutting.

Gear Shaping : Fine Grain WC+AlCrN, speed 150250 m/min, wet cutting.

Hard turning : ultrafine grain WC+TiAlN, speed 100200 m/min, dry cutting.

Testing and verification :

Microstructure : SEM (grain $0.22 \mu\text{m}$), EBSD (grain boundary stress $< 5\%$).

Performance : ASTM G65 ($< 0.040.05 \text{ mm}^3/\text{h}$), high temperature hardness ($> 1200 \text{ HV}$, 900°C).

Test : cutting force 600-1200 N, life 800-1500 min, Ra $0.4-0.8 \mu\text{m}$, AGMA 1012 grade.

7. Standards and specifications for cemented carbide wind turbine gear cutting tools

GB/T 183762014 : Porosity $< 0.01\%$.

GB/T 38502015 : Density deviation $\leq \pm 0.1 \text{ g/cm}^3$.

GB/T 38512015 : Strength 1.8-2.8 GPa.

GB/T 7997-2017 : Hardness 1400-2200 HV.

ASTM G65 : Wear rate $< 0.05 \text{ mm}^3/\text{h}$.

ISO 6508 : Hardness deviation $< \pm 50 \text{ HV}$.

ISO 1832 : Tooth form deviation $\leq \pm 0.01 \text{ mm}$.

AGMA 2015 : Tooth profile accuracy level 1012.

8. Conclusion

The cemented carbide wind turbine gear tools achieve high hardness (1800-2200 HV), wear resistance ($< 0.05 \text{ mm}^3/\text{h}$), heat resistance ($800-1000^\circ\text{C}$) and stability (lifetime 800-1500 minutes) by optimizing materials (ultra-fine grain WC $0.20.5 \mu\text{m}$, Co 6-12 wt %, TiAlN /AlCrN/GC4240 coating) and processes (HIP sintering 1350°C , 120 MPa, PVD/CVD coating $300-450^\circ\text{C}$).

The tool is suitable for roughing/finishing of wind power gears (42CrMo4, 18CrNiMo76, HRC 55-62, modulus 1040), with a speed of 100-500 m/min, an efficiency increase of 30-50%, and an accuracy of AGMA 1012, Ra $0.4-0.8 \mu\text{m}$. Optimizing ultrafine grains, composite coatings and precision grinding can reduce costs (500-2000 yuan per piece), and the challenges lie in large modulus processing (grinding costs increase by 20%) and coating adhesion ($> 80 \text{ N}$ required).

CTIA GROUP LTD uses nano WC ($D_{50} 0.20.5 \mu\text{m}$), HIP sintering (porosity $< 0.001\%$) and multi-layer PVD/CVD coating to develop high-performance hobs, gear shaping cutters and hard turning tools to meet the needs of wind power gear processing (lifespan > 1200 minutes, precision AGMA 12 level). The products have passed SEM, ASTM G65 and AGMA 2015 verification.

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appendix:

GB/T 18376-2001

Cemented Carbide Performance Test Method

1 Scope

This standard specifies the test methods for cemented carbide properties, including the test procedures for hardness, density, bending strength, fracture toughness, microstructure, magnetic properties, porosity and wear resistance. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and is also applicable to other similar cemented carbide materials (such as cemented carbide with TaC and VC added). This standard is not applicable to the performance test of coated cemented carbide.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For all referenced documents with dates, all subsequent amendments (excluding errata) or revisions are not applicable to this standard. For all referenced documents without dates, the latest version is applicable to this standard.

GB/T 228.1-2001 Tensile test of metallic materials Part 1: Room temperature test method

GB/T 230.1-2001 Rockwell hardness test for metallic materials Part 1: Test method (A, B, C scale)

GB/T 3848-2001 Method for determination of density of cemented carbide

GB/T 3850-2001 Determination method of flexural strength of cemented carbide

GB/T 3851-2001 Determination method of fracture toughness of cemented carbide

GB/T 5242-2001 Microstructure test method for cemented carbide

GB/T 7997-2001 Test method for Vickers hardness of cemented carbide

GB/T 9097-2001 Method for determination of magnetic properties of cemented carbide

3 Terms and definitions

This standard uses the following terms and definitions:

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

Hardness (HV): The ability of cemented carbide to resist the penetration of a Vickers indenter, expressed as Vickers hardness value (HV30), unit: kgf/mm^2 .

Density (ρ): The ratio of the mass of cemented carbide to its volume, expressed in g/cm^3 .

Bending strength (σ_{bb}): The maximum stress that a cemented carbide specimen withstands in a three-point bending test, expressed in MPa.

Fracture toughness (K_{Ic}): The ability of cemented carbide to resist crack growth, expressed in $\text{MPa} \cdot \text{m}^{1/2}$.

Microstructure: Distribution characteristics of WC grains, Co phase and pores in cemented carbide.

Magnetic properties: The magnetic saturation value (M_s) and coercive force (H_c) of cemented carbide reflect the magnetic characteristics of the Co phase.

Porosity: The volume percentage of pores in cemented carbide, classified into three categories: A, B, and C.

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4. Sample preparation

4.1 Sample requirements

The specimen should be of regular geometric shape (such as cuboid, cylinder), with a flat surface and no cracks, oxide layer or processing defects.

The sample size should meet the requirements of each performance test, such as:

Hardness test: surface area $>5 \times 5$ mm, thickness >2 mm.

Bending strength test: length $\times$ width $\times$ height = $20 \times 6.5 \times 5.25$ mm (± 0.05 mm).

Fracture toughness test: length $\times$ width $\times$ height = $20 \times 4 \times 2$ mm (± 0.02 mm).

The surface roughness of the sample is $Ra < 0.1 \mu\text{m}$ (polished).

4.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure the statistical representativeness of the test results.

If the result deviation is large ($>5\%$), the number of samples needs to be increased to 10.

4.3 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

5 Test Methods

5.1 Hardness test

5.1.1 Test Principle

The Vickers hardness method (HV30) is used. A load of 30 kgf is applied, and the Vickers indenter is pressed into the surface of the sample. The diagonal length of the indentation is measured and the hardness value is calculated.

5.1.2 Equipment

Vickers hardness tester, in accordance with GB/T 7997-2001 requirements.

Indenter: Standard Vickers diamond indenter, vertex angle $136^\circ (\pm 0.5^\circ)$.

Microscope: magnification 400 $\times$, resolution $<0.5 \mu\text{m}$.

5.1.3 Test steps

The sample surface was polished to $Ra < 0.1 \mu\text{m}$, cleaned and dried.

Apply a load of 30 kgf and hold the load for 10-15 s.

Measure the diagonal lengths of the indentation (d_1 , d_2) and take the average value ($d = (d_1 + d_2)/2$).

Calculate the hardness value:

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$$HV = \frac{1.8544 \times F}{d^2}$$

其中：F = 30 kgf, d 单位为 mm。

5.1.4 Result processing

5 points were measured for each sample and the average value was taken with a deviation of $\leq \pm 2\%$.
Hardness value range: HV 1200-2000 (depending on the brand, such as YG8 about HV 1500).

5.2 Density test

5.2.1 The test principle

is to use the Archimedes method to calculate the density by measuring the mass of the sample in air and in liquid.

5.2.2 Equipment

Analytical balance, accuracy ± 0.0001 g.

Liquid: distilled water, temperature 20°C ($\pm 1^\circ\text{C}$).

5.2.3 Test steps

Weigh the mass of the sample in air (m_1) with an accuracy of ± 0.0001 g.

Immerse the sample in distilled water and weigh the suspended mass (m_2).

Calculate the density:

$$\rho = \frac{m_1}{m_1 - m_2} \times \rho_{\text{水}}$$

Where: $\rho_{\text{water}} = 0.9982$ g/cm³

5.2.4 Result processing

Each sample was measured 3 times and the average value was taken with a deviation of $\leq \pm 0.01$ g/cm³.

Typical value: WC-10Co density is about 14.5-14.8 g/cm³.

5.3 Bending strength test

5.3.1 The test principle

is to use the three-point bending method. The specimen is subjected to force between two supporting points. The maximum load at fracture is recorded and the bending strength is calculated.

5.3.2 Equipment

Universal testing machine, load accuracy $\pm 0.5\%$.

Fixture: Span 14.5 mm (± 0.05 mm), support point diameter 2 mm.

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5.3.3 Test steps

Specimen dimensions: 20×6.5×5.25 mm (±0.05 mm).

Loading speed: 0.5 mm/min.

Record the breaking load F (N).

Calculate the flexural strength:

$$\sigma_{bb} = \frac{3FL}{2bh^2}$$

Where: L = 14.5 mm, b = 6.5 mm, h = 5.25 mm.

5.3.4 Result processing

Five samples were tested in each group and the average value was taken with a deviation of <±5%.

Typical value: YG8 flexural strength is about 2000-2400 MPa.

5.4 Fracture toughness test

5.4.1 Test Principle The single edge notched beam method (SEPB) is used to calculate the fracture toughness

K_{1c} by fracture of a prefabricated notched specimen in three-point bending.

5.4.2 Equipment

Universal testing machine, load accuracy ±0.5%.

Fixture: Span 16 mm (±0.05 mm).

Microscope: Measure notch depth with a resolution of <0.01 mm.

5.4.3 Test steps

Specimen size: 20×4×2 mm (±0.02 mm).

Prefabricated notch: depth 0.8-1.2 mm, width <0.2 mm.

Loading speed: 0.5 mm/min.

Record the breaking load F (N).

Calculate K_{1c} :

$$K_{1c} = Y \times \frac{3FL\sqrt{a}}{2BW^2}$$

Where: Y is the geometric factor (about 2.8-3.0), a is the notch depth, L = 16 mm, B = 4 mm, W = 2 mm.

5.4.4 Result processing

Five samples were tested in each group and the average value was taken with a deviation of <±5%.

Typical value: YG8 K_{1c} about 12-15 MPa·m^{1/2}.

5.5 Microstructure inspection

5.5.1 Test Principle

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The WC grain size, Co phase distribution and porosity are observed under a metallographic microscope, and the microstructure is graded and evaluated.

5.5.2 Equipment

Metallographic microscope, magnification 1000×, resolution <0.5 μm .

Polishing machine: Polish the specimen to Ra <0.05 μm .

Etchant: Murakami's reagent ($K_3Fe(CN)_6$ + NaOH solution).

5.5.3 Test steps

After polishing, the specimens were etched with Murakami's reagent for 10-20 s.

Observed at 1000× magnification:

WC Grain Size: Measure the average grain size (0.5-2 μm).

Co phase distribution: observe the uniformity.

Porosity classification: assessed in three categories: A, B, and C (A <0.02%, B <0.2%, and C is free carbon).

5.5.4 Result processing

Five fields of view were observed for each sample , and the grain size and porosity grade were recorded.

Typical values: YG8 grain size 0.8-1.2 μm , porosity A02-B00-C00.

5.6 Magnetic properties test

5.6.1 Test Principle

The magnetic saturation value (M_s) and coercive force (H_c) of cemented carbide are measured to reflect the Co phase content and microstructure characteristics.

5.6.2 Equipment

Magnetic property tester, accuracy ±1%.

Specimen: diameter 5 mm, height 10 mm (± 0.05 mm).

5.6.3 Test steps

The sample is demagnetized and placed in the tester.

Measure the magnetic saturation value M_s (unit: $\mu T \cdot m^3 / kg$).

Measure the coercive force H_c (unit: kA/m).

5.6.4 Result processing

Each sample was measured 3 times and the average value was taken with a deviation of <±2%.

Typical values: YG8 M_s is about 150-160 $\mu T \cdot m^3 / kg$, H_c is about 15-20 kA/m.

5.7 Wear resistance test

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5.7.1 Test Principle

The grinding wheel wear method is used to measure the mass loss of the sample under standard wear conditions and evaluate the wear resistance.

5.7.2 Equipment

Grinding wheel wear testing machine, grinding wheel material SiC , grain size 60#.

Load: 50 N.

5.7.3 Test steps

Specimen size: 10×10× 5 mm (±0.05 mm).

Grinding wheel speed: 200 r/min, test time: 30 min.

Weigh the mass of the sample before and after wear (m_1 , m_2) with an accuracy of ±0.0001 g.

Calculate the wear volume: $\Delta m = m_1 - m_2$

5.7.4 Result processing

Each sample was tested 3 times and the average value was taken with a deviation of <±5%.

Typical value: YG8 wear amount is about 0.05-0.08 g.

6 Evaluation of test results

The test results should meet the technical requirements of the cemented carbide grade (such as YG8: hardness HV 1450-1550, bending strength > 2000 MPa).

If the result deviation exceeds the allowable range (>5%), re-sampling and testing are required.

The test report should include: sample brand, test items, test conditions, result data and evaluation conclusions.

7 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, ambient temperature (20±5°C), humidity (50±10%).

Test results: hardness, density, flexural strength, fracture toughness, microstructure, magnetic properties, porosity, wear resistance, etc.

Deviation analysis: mean and deviation of each parameter.

Conclusion: Whether it meets the technical requirements.

Appendix A (Informative Appendix) Typical Carbide Performance Reference Values

Brand	Hardness (HV30)	Density(g/ cm ³)	Flexural strength(MPa)	Fracture toughness (K_{IC} , MPa·m ^{1/2})	Grain size (μm)	Porosity
YG6	1500-1600	14.8-15.0	1800-2200	14-16	0.8-1.2	A02-B00-C00
YG8	1450-1550	14.6-14.8	2000-2400	12-15	0.8-1.2	A02-B00-C00

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Brand	Hardness (HV30)	Density(g/ cm ³)	Flexural strength(MPa)	Fracture toughness (K _{1c} , MPa·m ^{1/2})	Grain size (μm)	Porosity
YT15	1550-1650	11.0-11.5	1600-2000	10-12	0.6-1.0	A02-B00- C00

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 20±5°C.

Humidity: 50±10%.

No vibration, no corrosive gas environment.

appendix:

GB/T 230.1-2001

Rockwell hardness test for metal materials

Part 1: Test methods (A, B, C scale)

1 Scope

This standard specifies the method for determining the hardness of metal materials at room temperature (10°C to 35°C) through the Rockwell hardness test (A, B, C scale), including test principles, equipment requirements, sample preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to the hardness test of steel, non-ferrous metals and cemented carbide (such as WC-Co).

HRA scale: suitable for cemented carbide and high hardness steel (hardness range 20-88 HRA).

HRB scale: Applicable to mild steel, non-ferrous metals (such as aluminum, copper) (hardness range 20-100 HRB).

HRC scale: Applicable to hardened steel and tempered steel (hardness range 20-70 HRC).

This standard is not applicable to the hardness test of thin-walled specimens (thickness <0.6 mm) or micro specimens.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 230.2-2001 Rockwell hardness test for metallic materials Part 2: Verification and calibration of hardness testers

GB/T 230.3-2001 Rockwell hardness test for metallic materials Part 3: Calibration of standard hardness blocks

GB/T 4340.1-1999 Vickers hardness test for metallic materials Part 1: Test method

GB/T 13683-1999 Terminology for testing mechanical properties of metallic materials

3 Terms and definitions

This standard adopts GB/T 13683-1999 and the following terms and definitions:

Rockwell Hardness (HR): The ability of a metal material to resist penetration by a Rockwell indenter. It is divided into scales such as HRA, HRB, and HRC and is calculated by the depth of the indentation.

Indentation depth (e): The depth formed when the Rockwell indenter is pressed into the sample surface, measured in mm, is inversely proportional to the hardness value .

Preload (F_0): The initial load applied to the indenter, in N (98.07 N for Rockwell test).

Total load (F): The total load applied to the indenter, in N (588.4 N for HRA and HRC, 980.7 N for HRB).

Hardness scale: A unit of hardness (such as HRC) defined by the combination of indenter type and load.

4 Test Principle

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The Rockwell hardness test is performed by pressing a diamond cone indenter (HRA, HRC) or a steel ball indenter (HRB) into the surface of a metal sample with a preload, then applying a total load, maintaining the load for a certain period of time, and then unloading to the preload, measuring the indentation depth difference (e), and calculating the Rockwell hardness value. The Rockwell hardness calculation formula is:

HRA, HRC:

$$HR = 100 - \frac{e}{0.002}$$

HRB:

$$HRB = 130 - \frac{e}{0.002}$$

in:

e is the indentation depth difference, in mm;

0.002 mm is the depth increment corresponding to each unit hardness value;

The HRA range is 20-88, the HRB range is 20-100, and the HRC range is 20-70.

5 Test equipment

5.1 Rockwell hardness tester

Conforms to the inspection and calibration requirements of GB/T 230.2-2001.

Load: Preload 98.07 N (10 kgf), total load is as follows:

HRA, HRC: 588.4 N (60 kgf).

HRB: 980.7 N (100 kgf).

Load accuracy: $\pm 0.5\%$.

Holding time control: 5 s to 15 s, deviation $\leq \pm 0.5$ s.

5.2 Indenter

Diamond cone indenter (HRA, HRC): apex angle $120^\circ (\pm 0.5^\circ)$, top spherical radius 0.2 mm (± 0.01 mm).

Steel ball indenter (HRB): diameter 1.5875 mm (1/16 inch, ± 0.005 mm), hardness $\geq$ HRC 60.

The surface of the indenter is free of defects and has clear edges (microscope inspection, resolution $< 0.5 \mu\text{m}$).

5.3 Measurement device

The hardness tester is equipped with digital or pointer reading system with an accuracy of ± 0.5 HR.

5.4 Calibration Block

Standard calibration blocks that meet the requirements of GB/T 230.3-2001:

HRA: 70-88 HRA, deviation $\leq \pm 0.5$ HRA.

HRB: 60-100 HRB, deviation $\leq \pm 1.0$ HRB.

HRC: 20-70 HRC, deviation $\leq \pm 0.5$ HRC.

The surface roughness of the calibration block is $R_a < 0.05 \mu\text{m}$.

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5.5 Environmental Control

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: cuboid, cylinder or other regular shape, test surface area > 5×5 mm, thickness as follows:

HRA, HRC: thickness > 0.8 mm.

HRB: thickness > 1.2 mm.

The test surface should be flat and free of cracks, oxide layers or machining defects.

Surface roughness Ra < 0.1 μm (polished).

The thickness of the specimen should meet the following requirements: thickness ≥ 10 × indentation depth (approximately 0.5 mm).

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large (>1 HR), the number of samples needs to be increased to 5.

6.3 Sample marking

The specimens shall be marked with batch number, brand (such as 45# steel, YG8) and test items, and the marking shall not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

7 Test steps

7.1 Equipment Calibration

Use the standard calibration block to calibrate the hardness tester and measure 3 times. The deviation is as follows:

HRA, HRC: < ±0.5 HR.

HRB: < ±1.0 HR.

Check the condition of the indenter to ensure there is no wear or defects.

7.2 Test conditions

Ambient temperature: 10°C to 35°C, 20±5°C recommended.

Relative humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

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7.3 Scale Selection

Select the scale according to the hardness of the material:

Cemented carbide, high hardness steel: HRA.

Mild steel, non-ferrous metals: HRB.

Quenched steel, tempered steel: HRC.

7.4 Test operation

Place the specimen on the hardness tester workbench, making sure the test surface is level.

Apply a preload of 98.07 N (10 kgf) to ensure that the indenter is in stable contact with the sample.

Apply the total load (588.4 N or 980.7 N) and hold the load for 5-15 s.

Unload to a preload of 98.07 N and record the hardness value (HRA, HRB or HRC).

5 points are measured for each sample, and the indentation spacing is as follows:

HRA, HRC: >3 times the indentation diameter (approximately 0.6 mm).

HRB: >4 times the indentation diameter (approximately 1.5 mm).

The indentation is >1 mm from the edge of the specimen.

7.5 Result calculation

hardness tester directly displays the HR value, or calculates it through the formula:

HRA, HRC:

$$HR = 100 - \frac{e}{0.002}$$

HRB:

$$HRB = 130 - \frac{e}{0.002}$$

Take the average value of 5 points as the hardness value of the sample, and the deviation is as follows:

HRA, HRC: $\leq \pm 1$ HR.

HRB: $\leq \pm 2$ HR.

8 Evaluation of test results

8.1 Hardness value range

The Rockwell hardness range of metal materials depends on the scale and material:

Cemented Carbide (YG8): HRA 87-89.

Hardened steel (45# steel, HRC 50): HRC 48-52.

Aluminum alloy (6061-T6): HRB 60-70.

8.2 Deviation Assessment

the 5 points are as follows, otherwise retesting is required:

HRA, HRC: $\leq \pm 1$ HR.

HRB: $\leq \pm 2$ HR.

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If the hardness value exceeds the material technical requirements, the reasons need to be analyzed (such as surface defects of the specimen and uneven microstructure).

8.3 Analysis of influencing factors

Surface quality: Surface roughness $R_a > 0.1 \mu\text{m}$ will result in lower hardness values (deviation > 1 HR).

Dwell time : A time < 5 s or > 15 s will affect the indentation depth (deviation ± 0.5 HR).

Specimen thickness: Thickness < 0.8 mm will lead to support effect and higher hardness values (deviation > 2 HR).

Microstructure: Uneven grain size ($> \pm 0.2 \mu\text{m}$) or high porosity can lead to hardness fluctuations ($> \pm 1$ HR).

9 Test Report

The test report should include the following:

Sample information: material type, brand, batch number, size.

Test conditions: equipment model, scale (HRA/HRB/HRC), load, holding time (5-15 s), ambient temperature (10°C to 35°C), humidity (30%-80%).

Test results: hardness value (HR), average value and deviation of each point.

Evaluation conclusion: whether it meets the technical requirements of the material.

Test date and operator's signature.

Appendix A (Informative Appendix) Rockwell hardness reference values of typical metal materials

Material Type	Brand/category	Rockwell hardness	Ruler	Typical Applications
Cemented Carbide	YG8	87-89	HRA	Cutting Tools
Hardened steel	45# (HRC 50)	48-52	HRC	Mechanical parts
Aluminum Alloy	6061-T6	60-70	HRB	Aerospace structures
Copper Alloy	H62	40-50	HRB	Electrical components

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation < 0.02 mm/m.

Appendix C (Informative Appendix) Comparison of Rockwell Hardness Scales

Ruler	Indenter Type	Total load(N)	Hardness range	Applicable Materials
HRA	Diamond cone	588.4	20-88	Hard alloy, high hardness steel
HRB	Steel ball (1.5875 mm)	980.7	20-100	Mild steel, non-ferrous metals
HRC	Diamond cone	588.4	20-70	Quenched steel, tempered steel

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Summarize

GB/T 230.1-2001 "Rockwell hardness test for metallic materials Part 1: Test method (A, B, C scale)" provides a standardized procedure for Rockwell hardness testing of metallic materials, ensuring the accuracy and repeatability of test results through standardized sample preparation, test steps and result evaluation. The implementation of this standard is applicable to the hardness evaluation of steel, non-ferrous metals and cemented carbide, providing reliable technical support for application fields such as machinery manufacturing, aerospace, and mold manufacturing.

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appendix:

GB/T 230.2-2001

Rockwell hardness test for metal materials

Part 2: Verification and calibration of hardness testers

1 Scope

This standard specifies the direct and indirect inspection and calibration methods for hardness testers (including A, B, C, D, E, F, G, H, K, N, T scales) for Rockwell hardness test of metallic materials, including inspection principles, equipment requirements, calibration steps, result evaluation, etc. This standard applies to the inspection and calibration of fixed and portable Rockwell hardness testers to ensure that the hardness testers meet the requirements of GB/T 230.1-2001 "Metallic Materials Rockwell Hardness Test Part 1: Test Method". This standard does not apply to the calibration of hardness testers for other hardness test methods.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 230.1-2001 Rockwell hardness test for metallic materials Part 1: Test method

GB/T 230.3-2001 Rockwell hardness test for metallic materials Part 3: Calibration of standard hardness blocks

GB/T 13683-1999 Terminology for testing mechanical properties of metallic materials

JIG 112-1999 Verification Procedure for Metal Rockwell Hardness Tester

3 Terms and definitions

This standard adopts GB/T 13683-1999 and the following terms and definitions:

Direct inspection: The process of verifying compliance with standard requirements by measuring parameters such as load, indenter geometry, penetration depth, and test cycle time of the hardness tester.

Indirect inspection: The process of verifying the measurement accuracy and repeatability of the hardness tester by measuring the hardness value on a standard block of known hardness using a standard hardness block.

Calibration: The process of adjusting the hardness tester's measuring system to make its measurement results consistent with the standard value .

Standard hardness block: A calibrated metal block with a known Rockwell hardness value used for indirect verification of a hardness tester.

4 Inspection and calibration principles

The inspection and calibration of Rockwell hardness tester is carried out by direct and indirect methods to ensure the measurement accuracy and reliability of the hardness tester:

Direct inspection: Verify whether the key parameters of the hardness tester (load, indenter shape, penetration depth, test cycle time) meet the requirements of GB/T 230.1-2001.

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Indirect inspection: Use a standard hardness block to measure the hardness value on a block of known hardness to evaluate the measurement deviation and repeatability of the hardness tester.

After calibration, the measurement deviation of the hardness tester should meet the following requirements:

HRA, HRC: $<\pm 1.0$ HR.

HRB: $<\pm 2.0$ HR.

5 Inspection and calibration equipment

5.1 Measuring instruments

Force measuring device: accuracy $\pm 0.5\%$, used to measure preload and total load.

Depth measuring device: accuracy ± 0.001 mm, used to measure the indentation depth.

Time measuring device: accuracy ± 0.1 s, used to measure the holding time .

Microscope or projector: magnification $50\times$ - $100\times$, resolution $<0.5\ \mu\text{m}$, for checking the indenter geometry.

5.2 Standard hardness block

In accordance with GB/T 230.3-2001, the hardness range is as follows:

HRA: 70-88 HRA, deviation $<\pm 0.5$ HRA.

HRB: 60-100 HRB, deviation $<\pm 1.0$ HRB.

HRC: 20-70 HRC, deviation $<\pm 0.5$ HRC.

The surface roughness of the standard hardness block is $R_a < 0.05\ \mu\text{m}$.

5.3 Environmental Control

Temperature: 10°C to 35°C , $20\pm 5^{\circ}\text{C}$ recommended.

Humidity: 30%-80%, $50\pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6 Inspection and calibration steps

6.1 Direct inspection

6.1.1 Load test

The measured preload is 98.07 N (10 kgf), with a deviation of $<\pm 1.0\%$.

Measuring total load:

HRA, HRC: 588.4 N (60 kgf), deviation $<\pm 0.5\%$.

HRB: 980.7 N (100 kgf), deviation $<\pm 0.5\%$.

The load is applied smoothly without shock or vibration.

6.1.2 Indenter inspection

Diamond cone indenter (HRA, HRC):

Vertex angle 120° ($\pm 0.5^{\circ}$).

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The top spherical radius is 0.2 mm (± 0.01 mm).

The surface is free of defects (microscope inspection, resolution $< 0.5 \mu\text{m}$).

Steel ball indenter (HRB):

Diameter 1.5875 mm (± 0.005 mm).

Hardness $\geq$ HRC 60.

No surface defects.

6.1.3 Depth measurement system inspection

Using a standard depth block, measure the indentation depth with a deviation of $\leq \pm 0.002$ mm.

6.1.4 Test cycle time inspection

Holding time 5-15 s, deviation $< \pm 0.5$ s.

Load application and unloading time < 2 s, no impact.

6.2 Indirect testing

Select a standard hardness block that matches the test scale (such as HRC 60).

Measure 5 times on the standard hardness block and record the hardness values.

Compute the mean and deviation:

HRA, HRC: mean value deviation $\leq \pm 1.0$ HR, single deviation $\leq \pm 1.5$ HR.

HRB: mean deviation $\leq \pm 2.0$ HR, single deviation $\leq \pm 3.0$ HR.

If the deviation exceeds the limit, the hardness tester needs to be calibrated.

6.3 Calibration

According to the direct and indirect test results, adjust the load and depth measurement system of the hardness tester or replace the indenter.

Repeat the indirect test after calibration to ensure that the deviation meets the requirements.

7 Evaluation of inspection and calibration results

7.1 Qualification determination

Direct inspection: parameters such as load, pressure head, depth, time, etc. all meet the requirements.

Indirect test:

HRA, HRC: mean value deviation $\leq \pm 1.0$ HR, repeatability $\leq \pm 1.5$ HR.

HRB: mean deviation $\leq \pm 2.0$ HR, repeatability $\leq \pm 3.0$ HR.

7.2 Non-conforming treatment

If the direct test fails, the hardness tester needs to be repaired (replace the indenter, adjust the load system, etc.).

If the indirect test fails, the hardness tester needs to be calibrated and retested.

If the test result fails twice in a row, the hardness tester shall not be used.

7.3 Analysis of influencing factors

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Load Deviation: Load deviation $> \pm 0.5\%$ will result in a hardness value that is too high or too low ($> \pm 1$ HR).

Indenter wear: Indenter wear can result in higher hardness values ($> \pm 1$ HR).

Environmental vibration: Vibration can cause depth measurement errors ($> \pm 0.5$ HR).

Standard block quality: Standard block hardness deviation $> \pm 0.5$ HR will affect the test results.

8 Inspection and calibration report

The inspection and calibration report should include the following:

Hardness tester information: model, number, manufacturer.

Test conditions: ambient temperature (10°C to 35°C), humidity (30%-80%), scale (HRA/HRB/HRC).

Test results:

Direct inspection: load, indenter geometry, depth, time and other parameters and deviations.

Indirect inspection: nominal value, measured value, average value and deviation of standard hardness block.

Calibration conclusion: whether it is qualified, calibration measures (such as adjusting the load, replacing the pressure head).

Inspection date and operator's signature.

Appendix A (Informative Appendix) Recommended values of standard hardness blocks

Ruler	Hardness range	Nominal value example	Deviation Request
HRA	70-88 HRA	85 HRA	$< \pm 0.5$ HRA
HRB	60-100 HRB	90 HRB	$< \pm 1.0$ HRB
HRC	20-70 HRC	60 HRC	$< \pm 0.5$ HRC

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C , $20 \pm 5^{\circ}\text{C}$ recommended.

Humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation < 0.02 mm/m.

Appendix C (Informative Appendix) Common Problems and Solutions

question	Possible causes	Workaround
Hardness value is high	Indenter wear	Replace the pressure head
Low hardness value	Insufficient load	Adjusting the load system
Poor repeatability	Environmental vibration	Improve the test environment
Inaccurate depth measurement	Depth measurement system failure	Calibrate or repair depth measurement systems

Summarize

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GB/T 230.2-2001 "Rockwell hardness test for metallic materials Part 2: Verification and calibration of hardness testers" provides a standardized procedure for the inspection and calibration of Rockwell hardness testers, ensuring the measurement accuracy and reliability of hardness testers through direct and indirect inspection methods. The implementation of this standard helps to improve the accuracy and consistency of hardness test results and is applicable to the management of hardness testers in the fields of machinery manufacturing, material testing, etc.

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appendix:

GB/T 230.3-2001 Metallic Materials

Rockwell hardness test Part 3: Calibration of standard hardness blocks

1 Scope

This standard specifies the calibration method of standard hardness blocks (including A, B, C, D, E, F, G, H, K, N, T scales) for Rockwell hardness test of metal materials, including calibration principles, equipment requirements, calibration steps, result evaluation, etc. This standard is applicable to the calibration of Rockwell hardness standard blocks that are newly manufactured or in use to ensure that their hardness values meet the requirements of GB/T 230.1-2001 and GB/T 230.2-2001. This standard is not applicable to the calibration of standard blocks for other hardness test methods.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 230.1-2001 Rockwell hardness test for metallic materials Part 1: Test method

GB/T 230.2-2001 Rockwell hardness test for metallic materials Part 2: Verification and calibration of hardness testers

GB/T 13683-1999 Terminology for testing mechanical properties of metallic materials

JJG 112-1999 Verification Procedure for Metal Rockwell Hardness Tester

3 Terms and definitions

This standard adopts GB/T 13683-1999 and the following terms and definitions:

Standard hardness block: A calibrated metal block with a known Rockwell hardness value used for indirect verification and calibration of hardness testers.

Calibration: The process of determining the hardness value of a standard hardness block using a standard hardness tester or a traceable device with higher accuracy.

Hardness uniformity: The distribution consistency of hardness values on the surface of a standard hardness block, expressed by the deviation of the measuring points.

Traceability: The process of linking the hardness value of a hardness reference block to a national or international hardness benchmark through a calibration chain.

4 Calibration Principle

The calibration of the standard hardness block is carried out by using a calibrated high-precision Rockwell hardness tester (in accordance with GB/T 230.2-2001) to perform multiple hardness measurements on the surface of the standard block, calculate the average hardness value and hardness uniformity, and ensure that its hardness value is accurate and reliable. The calibration results must be traceable to national or international hardness standards to ensure the consistency and comparability of the measurements.

5. Calibration equipment

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5.1 Standard Rockwell hardness tester

It complies with the requirements of GB/T 230.2-2001 and has been directly and indirectly tested.

Measurement deviation:

HRA, HRC: $<\pm 0.5$ HR.

HRB: $<\pm 1.0$ HR.

The hardness tester needs to be traceable to a national or international hardness standard.

5.2 Indenter

Diamond cone indenter (HRA, HRC): apex angle $120^\circ (\pm 0.5^\circ)$, top spherical radius 0.2 mm (± 0.01 mm).

Steel ball indenter (HRB): diameter 1.5875 mm (± 0.005 mm), hardness $\geq$ HRC 60.

The indenter surface was free of defects (microscope inspection, resolution $<0.5 \mu\text{m}$).

5.3 Measuring instruments

Vernier caliper: accuracy ± 0.02 mm, used to measure the size of standard blocks.

Surface roughness meter: measure surface roughness, accuracy $\pm 0.01 \mu\text{m}$.

5.4 Environmental Control

Temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6 Standard hardness block requirements

6.1 Materials and manufacturing

Standard block material: high-quality steel or other metal with stable hardness and homogeneous microstructure without segregation or porosity.

Size: Thickness ≥ 6 mm, test surface area $\geq 30 \times 30$ mm.

Surface roughness: $R_a < 0.05 \mu\text{m}$ (polished).

The test surface should be flat with a parallelism of <0.01 mm.

6.2 Hardness range

HRA: 70-88 HRA.

HRB: 60-100 HRB.

HRC: 20-70 HRC.

6.3 Marking

The standard block should be marked with the nominal hardness value, scale, production batch number, manufacturing unit and other information, and the marking should not affect the test area.

7 Calibration steps

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7.1 Calibration Preparation

Check the status of the standard hardness tester to ensure that it meets the requirements of GB/T 230.2-2001.

Clean the standard hardness block, remove oil and dust with anhydrous ethanol, and use it after drying.

Measure the size and parallelism of the standard block and record the surface roughness.

7.2 Calibration conditions

Ambient temperature: 10°C to 35°C, 20±5°C recommended.

Relative humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

7.3 Calibration Operation

Five measuring points are evenly distributed on the test surface of the standard hardness block, with the point spacing >3 times the indentation diameter (HRA, HRC about 0.6 mm, HRB about 1.5 mm), and the distance from the edge is >2.5 mm.

Use a standard hardness tester to measure the hardness values at 5 points and record the results of each measurement.

Holding time : 5-15 s, deviation <±0.5 s.

7.4 Result calculation

计算 5 个点的平均硬度值:

$$\overline{HR} = \frac{HR_1 + HR_2 + HR_3 + HR_4 + HR_5}{5}$$

计算硬度均匀性 (最大偏差) :

$$\Delta HR = HR_{\max} - HR_{\min}$$

Qualification determination:

HRA, HRC: mean deviation <±0.5 HR, homogeneity <1.0 HR.

HRB: mean deviation <±1.0 HR, homogeneity <2.0 HR.

7.5 Tracing

The calibration results need to be traceable to a national or international hardness standard and the traceability chain should be documented (e.g. through a national metrology institute).

8 Evaluation of calibration results

8.1 Qualification

Average hardness value deviation:

HRA, HRC: <±0.5 HR.

HRB: <±1.0 HR.

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Hardness uniformity:

HRA, HRC: <1.0 HR.

HRB: <2.0 HR.

Surface roughness Ra <0.05 μm , parallelism <0.01 mm.

8.2 Non-conforming treatment

If the mean value deviation or uniformity exceeds the limit, the standard block shall not be used.

Analyze the reasons (such as uneven material, poor surface quality), remanufacture or process the standard block and then calibrate.

8.3 Analysis of influencing factors

Material homogeneity: Microstructural inhomogeneities (grain size > $\pm 0.2 \mu\text{m}$) can lead to poor homogeneity (>1 HR).

Surface quality: Roughness Ra >0.05 μm will result in fluctuations in hardness values (> ± 0.5 HR).

Hardness tester accuracy: Hardness tester deviation > ± 0.5 HR will affect the calibration result.

Environmental vibration: Vibration can cause measurement errors (> ± 0.5 HR).

9 Calibration certificate

The calibration certificate should contain the following:

Standard hardness block information: nominal hardness value, scale, production batch number, manufacturing unit.

Calibration conditions: hardness tester model, ambient temperature (10°C to 35°C), humidity (30%-80%).

Calibration results: hardness value, average value, uniformity, deviation at 5 points.

Traceability information: traceability chain and national/international benchmarks.

Calibration conclusion: whether qualified or not.

Calibration date and operator signature.

Appendix A (Informative Appendix) Examples of calibration values of standard hardness blocks

Ruler	Nominal value	Measurement value (HR)	Average(HR)	Uniformity (HR)	Deviation (HR)
HRA	85	85.1, 85.0, 84.9, 85.2, 85.0	85.0	0.3	± 0.1
HRB	90	90.2, 89.8, 90.0, 90.1, 89.9	90.0	0.4	± 0.2
HRC	60	60.1, 60.0, 59.9, 60.2, 60.0	60.0	0.3	± 0.1

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20 $\pm$ 5°C recommended.

Humidity: 30%-80%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

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Appendix C (Informative Appendix) Common Problems and Solutions

question	Possible causes	Workaround
Poor hardness uniformity	Inhomogeneous material microstructure	Replace material or reheat treat
Mean value deviation exceeded	Hardness tester is not accurate enough	Calibration of hardness tester
Surface roughness exceeds the standard	Insufficient polishing	Re-polishing
Large fluctuations in measured values	Environmental vibration	Improve the test environment

Summarize

GB/T 230.3-2001 "Rockwell hardness test for metallic materials Part 3: Calibration of standard hardness blocks" provides a standardized procedure for the calibration of Rockwell hardness standard blocks, and ensures the accuracy and reliability of the hardness values of the standard blocks through standardized calibration steps and result evaluation. The implementation of this standard helps to improve the traceability and consistency of hardness testing, and is applicable to fields such as material testing and metrological calibration.

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appendix:

GB/T 3848-2001

Method for determination of density of cemented carbide

1 Scope

This standard specifies the method for determining the density of cemented carbide materials. The density is calculated by weighing the mass of the sample in air and in liquid using the Archimedean principle. This standard is applicable to cemented carbides with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbides with other carbides (such as TaC, TiC, VC). This standard is not applicable to porous or cracked cemented carbide specimens, nor is it applicable to the density determination of other materials (such as steel or ceramics).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 3847-1983 Method for preparation of cemented carbide specimens

GB/T 3850-1983 Terminology of cemented carbide

JJG 196-1990 Verification procedures for commonly used glass measuring instruments

3 Terms and definitions

This standard adopts GB/T 3850-1983 and the following terms and definitions:

Density (ρ): The mass of a cemented carbide specimen divided by its volume, expressed in g/cm^3 .

Archimedes principle: When a sample is immersed in a liquid, the buoyancy it experiences is equal to the mass of the liquid it displaces, and the buoyancy is equal to the difference between the mass of the sample in the air and the mass in the liquid.

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4. Determination principle

The density of cemented carbide is determined based on the Archimedean principle and is calculated by the following steps:

Weigh the mass of the sample in air (m_1);

Weigh the mass of the sample in the liquid (usually deionized water) (m_2);

The sample volume is calculated based on the buoyancy, and the sample density is calculated based on the liquid density.

The density calculation formula is:

$$\rho = \frac{m_1}{m_1 - m_2} \times \rho_0$$

in:

ρ is the sample density, in g/cm^3 ;

m_1 is the mass of the sample in air, in g;

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m_2 is the mass of the sample in the liquid, in g;

ρ_0 is the density of the liquid in g/cm^3 (0.9982 g/cm^3 for deionized water at 20°C).

5. Measurement equipment

5.1 Analytical balance

Accuracy: $\pm 0.1 \text{ mg}$.

Measuring range: $0\text{--}200 \text{ g}$.

Equipped with a suspension device to weigh the mass of the sample in the liquid.

5.2 Liquid medium

Deionized water, purity meets the requirements of GB/T 6682-1992.

Temperature: $20 \pm 5^\circ\text{C}$, measurement accuracy $\pm 0.1^\circ\text{C}$.

cm^3 at 20°C).

5.3 Auxiliary equipment

Thermometer: Accuracy $\pm 0.1^\circ\text{C}$.

Fine metal wire: diameter $< 0.1 \text{ mm}$, used to suspend the sample.

Beaker: Capacity $100\text{--}500 \text{ mL}$, in accordance with JJG 196-1990.

Ultrasonic cleaner: frequency 40 kHz , used to clean samples.

5.4 Environmental Control

Temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Humidity: $30\%\text{--}80\%$, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: regular geometric shape (such as cuboid, cylinder), mass $5\text{--}50 \text{ g}$.

The surface of the specimen should be flat and free of cracks, pores or oxide layers.

The specimens should comply with the preparation requirements of GB/T 3847-1983.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large ($> 0.02 \text{ g/cm}^3$), the number of samples needs to be increased to 5 .

6.3 Sample cleaning

Use anhydrous ethanol or acetone to clean the surface of the sample to remove oil and dust.

Clean in an ultrasonic cleaner for 5 min (frequency 40 kHz).

After washing, dry at 60°C for 30 min or air dry to constant weight.

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6.4 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

7 Measurement steps

7.1 Equipment Calibration

The analytical balance was calibrated using standard weights with a deviation of $\leq \pm 0.1$ mg. Measure the liquid temperature and record the density of the deionized water (see Appendix A).

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 5^{\circ}\text{C}$ recommended.

Relative humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Measurement operation

Weigh the mass of the sample in air (m_1) using an analytical balance and record to 0.1 mg.

The sample was suspended by a thin metal wire and immersed in deionized water, ensuring that the sample was completely immersed and free of bubbles.

Weigh the mass of the sample in deionized water (m_2) and record to 0.1 mg.

Each sample was measured 3 times and the average value was taken.

Record the liquid temperature and determine the liquid density (ρ_0) from a table.

7.4 Result calculation

Calculate the sample density:

$$\rho = \frac{m_1}{m_1 - m_2} \times \rho_0$$

The average value of 3 measurements is taken as the sample density, with a deviation of $\leq \pm 0.02$ g/cm³.

8 Evaluation of measurement results

8.1 Density range

The density range of cemented carbide depends on the grade:

YG6 (6% Co): 14.6-14.9 g/cm³.

YG8 (8% Co): 14.5-14.8 g/cm³.

YT15 (5% Co + TiC): 12.8-13.2 g/cm³.

8.2 Deviation Assessment

The density deviation of the three measurements is $\leq \pm 0.02$ g/cm³, otherwise the test needs to be repeated.

If the density value is outside the expected range, the cause needs to be analyzed (such as sample

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porosity, incomplete cleaning).

8.3 Analysis of influencing factors

Bubble adhesion: Bubbles on the sample surface will cause the m_{20} to be too large and the density to be too low (deviation $> 0.05 \text{ g/cm}^3$).

Liquid temperature: Temperature deviation $> \pm 5^\circ\text{C}$ affects ρ_0 , density deviation $> 0.01 \text{ g/cm}^3$.

Specimen porosity: Porosity $> 0.5\%$ results in a lower density (deviation $> 0.1 \text{ g/cm}^3$).

Balance accuracy: Balance deviations $> \pm 0.1 \text{ mg}$ affect the density calculation (deviation $> 0.01 \text{ g/cm}^3$).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, liquid medium (deionized water), temperature ($^\circ\text{C}$), humidity (%).

Test results: mass in air (m_1), mass in liquid (m_2), density (ρ), average value and deviation.

Evaluation conclusion: whether it meets the expected range.

Test date and operator's signature.

Appendix A (Informative Appendix) Table of the relationship between deionized water density and temperature

Temperature ($^\circ\text{C}$)	Density (ρ_0) (g/cm^3)
15	0.9991
20	0.9982
25	0.9970
30	0.9957

Appendix B (Informative Appendix) Typical Carbide Density Reference Values

Brand	Co content (wt %)	Density(g/cm^3)	Typical Applications
YG6	6	14.6-14.9	Mining drill bits
YG8	8	14.5-14.8	Cutting Tools
YT15	5	12.8-13.2	Finishing tools

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $< 0.02 \text{ mm/m}$.

Summarize

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GB/T 3848-2001 "Determination of density of cemented carbide" provides a standardized procedure for the determination of cemented carbide density, and ensures the accuracy and repeatability of the test results through the Archimedean principle. The implementation of this standard helps the quality control of cemented carbide materials and provides reliable technical support for high-performance application fields such as cutting tools and mining drills.

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appendix:

GB/T 3850-2001

Determination method of bending strength of cemented carbide

1 Scope

This standard specifies the determination method of the flexural strength of cemented carbide materials. The three-point bending test method is used to calculate the flexural strength (transverse rupture strength, TRS) by applying a load until the specimen breaks. This standard is applicable to cemented carbides with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbides with other carbides (such as TaC, TiC, VC). This standard is not applicable to porous or cracked cemented carbide specimens, nor is it applicable to the determination of flexural strength of other materials (such as steel or ceramics).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 3847-1983 Method for preparation of cemented carbide specimens

GB/T 3851-1983 Cemented Carbide Terminology

GB/T 230.1-2001 Rockwell hardness test for metallic materials Part 1: Test method

3 Terms and definitions

This standard adopts GB/T 3851-1983 and the following terms and definitions:

Flexural strength (σ_{bb}) or transverse rupture strength (TRS): The maximum stress that a cemented carbide specimen can withstand in a three-point bending test, expressed in MPa.

Three-point bending test: A test method in which the specimen is placed on two supporting points and a load is applied to the center until the specimen breaks.

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

The three-point bending test method is used to determine the bending strength of cemented carbide. The sample is placed on two supporting points and a load is applied to the center of the sample until the sample breaks. The maximum breaking load (P) is recorded and the bending strength is calculated based on the sample size and span. The bending strength calculation formula is:

$$\sigma_{bb} = \frac{3PL}{2bh^2}$$

in:

σ_{bb} is the flexural strength, in MPa;

P is the breaking load, in N;

L is the support point span, in mm;

b is the width of the specimen, in mm;

h is the sample thickness in mm.

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5. Measurement equipment

5.1 Universal testing machine

Load range: 0-50 kN , accuracy $\pm 0.5\%$.

Loading speed control: 0.5-5 mm/min, deviation $< \pm 0.1$ mm/min.

Equipped with a three-point bending fixture, the span of the support points is adjustable.

5.2 Fixture

Support and loading point diameter: 2 mm (± 0.02 mm).

Support point span: 30 mm (± 0.05 mm).

The surface hardness of the support point and loading point is $\geq \text{HRC } 60$, and the surface roughness is $R_a < 0.1 \mu\text{m}$.

5.3 Measurement tools

Vernier caliper: accuracy ± 0.02 mm, used to measure sample size.

Micrometer: Accuracy ± 0.001 mm, used for precise thickness measurement.

5.4 Environmental Control

Temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, dimensions $35 \times 5 \times 5$ mm (± 0.1 mm).

The surface of the specimen should be flat and free of cracks, pores or oxide layers.

The specimens should comply with the preparation requirements of GB/T 3847-1983.

The surface roughness of the sample is $R_a < 0.2 \mu\text{m}$ (polished).

The four long sides of the specimen were chamfered $0.1 \times 45^\circ$ to reduce stress concentration.

6.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure statistical representativeness.

If the result deviation is large ($> 10\%$), the number of samples needs to be increased to 8.

6.3 Sample cleaning

Use anhydrous ethanol to clean the surface of the sample to remove oil, dust, and use it after drying.

6.4 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

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6.5 Sample measurement

The width (b) and thickness (h) of the specimens were measured using a vernier caliper and a micrometer with an accuracy of ± 0.02 mm.

7 Measurement steps

7.1 Equipment Calibration

The testing machine was calibrated using a standard force sensor with a load deviation of $< \pm 0.5\%$. Check the span of the fixture support points, the deviation is $< \pm 0.05$ mm.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 5^{\circ}\text{C}$ recommended.

Relative humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Measurement operation

Place the specimen on the two supporting points of the three-point bending fixture, ensuring that the specimen is horizontal and the span L is 30 mm (± 0.05 mm).

Adjust the loading point so that it is located in the center of the specimen.

Apply load at a speed of 1 mm/min (± 0.1 mm/min).

Record the maximum load (P) when the specimen breaks, in N.

Each sample was tested once and repeated 5-8 times to ensure the stability of the results.

7.4 Result calculation

Calculate the flexural strength:

$$\sigma_{bl} = \frac{3PL}{2bh^2}$$

Take the average value of 5-8 samples, with a deviation of $< \pm 10\%$.

8 Evaluation of measurement results

8.1 Bending strength range

The bending strength range of cemented carbide depends on the grade:

YG6 (6% Co): 2000-2500 MPa.

YG8 (8% Co): 1800-2200 MPa.

YT15 (5% Co + TiC): 1300-1600 MPa.

8.2 Deviation Assessment

of 5-8 specimens is $< \pm 10\%$, otherwise retesting is required.

If the flexural strength value is outside the expected range, the cause needs to be analyzed (such as specimen defects, misaligned fixtures).

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8.3 Analysis of influencing factors

Specimen defects: Porosity > 0.5% or microcracks will result in lower strength (deviation > 15%).
Fixture alignment: Misalignment of support points can lead to stress concentration and low strength (deviation > 10%).
Loading speed: Speed > 5 mm/min will result in higher strength (deviation > 5%).
Microstructure: Uneven grain size ($>\pm 0.2\ \mu\text{m}$) or uneven distribution of the bonding phase will reduce the strength (deviation > 10%).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, span (L), loading speed, ambient temperature (10°C to 35°C), humidity (30%-80%).

σ_{bb}), average value and deviation of each specimen .

Evaluation conclusion: whether it meets the expected range.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Bending Strength of Typical Cemented Carbides

Brand	Co content (wt %)	Flexural strength(MPa)	Typical Applications
YG6	6	2000-2500	Mining drill bits
YG8	8	1800-2200	Cutting Tools
YT15	5	1300-1600	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation < 0.02 mm/m.

Summarize

GB/T 3850-2001 "Determination of Flexural Strength of Cemented Carbide" provides a standardized procedure for the determination of flexural strength of cemented carbide, and ensures the accuracy and repeatability of the test results through the three-point bending test method. The implementation of this standard helps to evaluate the mechanical properties of cemented carbide materials and provides reliable technical support for high-performance application fields such as cutting tools and mining drills.

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appendix:

GB/T 3851-2001

Determination method of fracture toughness of cemented carbide

1 Scope

This standard specifies the determination method of fracture toughness (expressed as stress intensity factor K_{IC}) of cemented carbide materials. The single-edge notched beam (SENB) test method is used to calculate the fracture toughness by applying load to the specimen. This standard is applicable to cemented carbides with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbides with other carbides (such as TaC, TiC, VC). This standard is not applicable to porous or cracked cemented carbide specimens, nor is it applicable to the determination of fracture toughness of other materials (such as steel or ceramics).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 3847-1983 Method for preparation of cemented carbide specimens

GB/T 3850-1983 Terminology of cemented carbide

GB/T 230.1-2001 Rockwell hardness test for metallic materials Part 1: Test method

3 Terms and definitions

This standard adopts GB/T 3850-1983 and the following terms and definitions:

Fracture toughness (K_{IC}): The ability of cemented carbide specimens to resist fracture in a cracked state, expressed by the critical stress intensity factor, with the unit of $\text{MPa} \cdot \text{m}^{1/2}$.

Single-edge notched beam (SENB) test: A test method in which a pre-crack is created on one side of the specimen and a load is applied until fracture using the three-point bending method.

Pre-crack: An initial crack prepared by machining or fatigue pre-cracking to simulate actual defects.

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

The fracture toughness of cemented carbide is determined by the single-edge notched beam (SENB) test method. A prefabricated crack is made on one side of the sample, the sample is placed on a three-point bending fixture, a load is applied until the sample breaks, the maximum fracture load (P) is recorded, and the fracture toughness is calculated based on the sample size, crack length and span. The fracture toughness calculation formula is:

$$K_{IC} = \frac{PL}{BW^{3/2}} \cdot Y$$

in:

K_{IC} is the fracture toughness, in $\text{MPa} \cdot \text{m}^{1/2}$;

P is the breaking load, in N;

L is the support point span, in mm;

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B is the sample thickness, in mm;

W is the width of the specimen, in mm;

Y is a geometric factor that depends on the relative crack length a/W (see Appendix A).

5. Measurement equipment

5.1 Universal testing machine

Load range: 0-50 kN , accuracy $\pm 0.5\%$.

Loading speed control: 0.05-0.5 mm/min, deviation $< \pm 0.01$ mm/min.

Equipped with a three-point bending fixture, the span of the support points is adjustable.

5.2 Fixture

Support and loading point diameter: 2 mm (± 0.02 mm).

Support point span: 20 mm (± 0.05 mm).

The surface hardness of the support point and loading point is $\geq \text{HRC } 60$, and the surface roughness is $R_a < 0.1 \mu\text{m}$.

5.3 Crack preparation equipment

Precision cutting machine: used for processing initial incisions, with incision width < 0.2 mm and depth accuracy of ± 0.01 mm.

Microscope: magnification $50\times$ - $200\times$, resolution $< 0.5 \mu\text{m}$, used to measure crack length.

5.4 Measurement tools

Vernier caliper: accuracy ± 0.02 mm, used to measure sample size.

Micrometer: Accuracy ± 0.001 mm, used for precise thickness measurement.

5.5 Environmental Control

Temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, dimensions $20 \times 4 \times 2.5$ mm (± 0.1 mm).

The surface of the specimen should be flat and free of cracks or oxide layer.

The specimens should comply with the preparation requirements of GB/T 3847-1983.

Surface roughness $R_a < 0.2 \mu\text{m}$ (polished).

6.2 Prefabricated cracks

Cut position: located at the bottom center of the specimen, with a length a of 0.2-0.5 times the width W of the specimen (i.e. $a/W = 0.2 - 0.5$).

Incisor width: < 0.2 mm, incision tip blunted to 0.05 mm radius.

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The cutouts can be prepared by machining or fatigue pre-cracking, fatigue pre-cracking is recommended to simulate natural cracks.

6.3 Number of samples

The number of samples in each batch shall not be less than 5 to ensure statistical representativeness. If the results have a large deviation (>10%), the number of samples needs to be increased to 8 .

6.4 Sample cleaning

Use anhydrous ethanol to clean the surface of the sample to remove oil, dust, and use it after drying.

6.5 Sample measurement

The specimen width (W), thickness (B) and crack length (a) were measured using a vernier caliper and micrometer with an accuracy of ± 0.02 mm.

7 Measurement steps

7.1 Equipment Calibration

The testing machine was calibrated using a standard force sensor with a load deviation of $\leq \pm 0.5\%$. Check the span of the fixture support points, the deviation is $\leq \pm 0.05$ mm.

The crack length measurement was calibrated using a microscope with a deviation of $\leq \pm 0.01$ mm.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 5^{\circ}\text{C}$ recommended.

Relative humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Measurement operation

The specimen was placed on the two supporting points of the three-point bending fixture with a span L of 20 mm (± 0.05 mm).

Adjust the loading point so that it is located in the center of the specimen and aligned with the prefabricated crack.

Apply load at a speed of 0.1 mm/min (± 0.01 mm/min).

Record the maximum load (P) when the specimen breaks, in N.

Each sample was tested once and repeated 5-8 times to ensure the stability of the results.

7.4 Result calculation

Calculate the geometric factor Y (based on the a/W table, see Appendix A).

Calculate the fracture toughness:

$$K_{IC} = \frac{PL}{BW^{3/2}} \cdot Y$$

Take the average value of 5-8 samples , with a deviation of $\leq \pm 10\%$.

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8 Evaluation of measurement results

8.1 Fracture toughness range

The fracture toughness range of cemented carbide depends on the grade:

YG6 (6% Co): $10-12 \text{ MPa}\cdot\text{m}^{1/2}$.

YG8 (8% Co): $12-15 \text{ MPa}\cdot\text{m}^{1/2}$.

YT15 (5% Co + TiC): $8-10 \text{ MPa}\cdot\text{m}^{1/2}$.

8.2 Deviation Assessment

of 5-8 specimens is $\leq \pm 10\%$, otherwise retesting is required.

If the fracture toughness value is outside the expected range, the cause (such as crack quality, specimen defects) needs to be analyzed.

8.3 Analysis of influencing factors

Crack quality: K_{IC} can be too high (deviation $> 10\%$) if the cut width is $> 0.2 \text{ mm}$ or the tip is not uniformly blunted.

Fixture alignment: Misaligned support points will result in uneven stress distribution and low K_{IC} (deviation $> 5\%$).

Loading speed: Speed $> 0.5 \text{ mm/min}$ will affect the fracture behavior and the K_{IC} will be too high (deviation $> 5\%$).

Microstructure: Uneven distribution of the bonding phase (Co content fluctuation $> \pm 0.5\%$) will reduce K_{IC} (deviation $> 10\%$).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size, crack length (a).

Test conditions: equipment model, span (L), loading speed, ambient temperature (10°C to 35°C), humidity (30%-80%).

K_{IC}), average value and deviation of each specimen.

Evaluation conclusion: whether it meets the expected range.

Test date and operator's signature.

Appendix A (Informative Appendix) Geometric Factor Y Table

a/W	Y
0.2	1.90
0.3	2.10
0.4	2.40
0.5	2.80

注: Y 值为近似值, 实际应用中可参考标准提供的详细表或插值计算。

Appendix B (Informative Appendix) Reference values of fracture toughness of typical

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cemented carbides

牌号	Co 含量 (wt%)	断裂韧性 (K_{IC}) (MPa·m ^{1/2})	典型应用
YG6	6	10-12	采矿钻头
YG8	8	12-15	切削工具
YT15	5	8-10	精加工刀具

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

GB/T 3851-2001 "Method for determination of fracture toughness of cemented carbide" provides a standardized procedure for the determination of fracture toughness of cemented carbide, and ensures the accuracy and repeatability of the test results through the single-sided notched beam test method. The implementation of this standard helps to evaluate the crack resistance of cemented carbide materials and provides reliable technical support for high-performance application fields such as cutting tools and mining drills.

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appendix:

GB/T 9097-2001

Determination method of magnetic properties of cemented carbide

1 Scope

This standard specifies the determination method of magnetic properties of cemented carbide materials, including the determination of magnetic saturation intensity (magnetization intensity) and coercive force (H_c), using electromagnetic induction method and hysteresis loop method. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC , TiC , VC). This standard is not applicable to non-ferromagnetic materials or cemented carbide without cobalt.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 3847-1983 Method for preparation of cemented carbide specimens

GB/T 3850-1983 Terminology of cemented carbide

GB/T 3848-2001 Method for determination of density of cemented carbide

3 Terms and definitions

This standard adopts GB/T 3850-1983 and the following terms and definitions:

Magnetic saturation intensity (M_s): The magnetic intensity of a cemented carbide specimen when it reaches magnetic saturation under a sufficiently strong external magnetic field, expressed in kA/m or emu/g.

Coercive force (H_c): After the cemented carbide sample is magnetized, the magnetic field strength required for the external magnetic field to reverse and make the magnetization intensity of the sample zero, the unit is kA/m.

Hysteresis loop: A closed curve formed when the magnetization intensity of a sample changes with the magnetic field strength under the action of an external magnetic field, which is used to measure coercive force.

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

The determination of the magnetic properties of cemented carbide is based on the electromagnetic induction method and the hysteresis loop method:

Magnetic saturation intensity (M_s): The magnetic saturation intensity of the sample is measured by placing the sample in a strong magnetic field (usually >1000 kA/m) to make the cobalt phase reach magnetic saturation. The magnetic saturation intensity is related to the cobalt content and can be used to evaluate the quality of the cobalt phase .

Coercive force (H_c) determination: By drawing the hysteresis loop of the sample, record the

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magnetic field strength that makes the magnetization intensity drop to 0 when the external magnetic field is reversed, that is, the coercive force. The coercive force reflects the magnetic microstructure and grain size of the material.

5. Measurement equipment

5.1 Magnetic property tester

Equipment type: Hysteresis loop instrument (such as oscillating sample magnetometer VSM or electromagnetic force method instrument).

Magnetic field range: 0-2000 kA/m, accuracy $\pm 0.5\%$.

Magnetization intensity measurement range: 0-1000 kA/m or 0-200 emu/g, accuracy $\pm 0.1\%$.

Equipped with electromagnets or superconducting magnets to provide a uniform magnetic field.

5.2 Auxiliary equipment

Analytical balance: accuracy ± 0.1 mg, used to weigh the sample mass.

Vernier caliper: accuracy ± 0.02 mm, used to measure sample size.

5.3 Environmental Control

Temperature: 10°C to 35°C, 20 ± 5 °C recommended.

Humidity: 30%-80%, recommended <60%.

No vibration, no external magnetic field interference (ambient magnetic field <0.1 kA/m).

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size is 6 $\times$ 6 $\times$ 10 mm or 6 mm in diameter and 10 mm in height.

Sample mass: 0.5-5 g, depending on equipment requirements.

The surface of the specimen should be flat and free of cracks or oxide layer.

The specimens should comply with the preparation requirements of GB/T 3847-1983.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large ($>\pm 2\%$), the number of samples needs to be increased to 5.

6.3 Sample cleaning

Use anhydrous ethanol to clean the surface of the sample to remove oil, dust, and use it after drying.

6.4 Sample marking

The samples should be marked with batch number and brand name, and the marking should not affect the test area.

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6.5 Sample measurement

Weigh the sample mass with an accuracy of ± 0.001 g.

Measure the sample size with an accuracy of ± 0.02 mm.

7 Measurement steps

7.1 Equipment Calibration

Use standard samples (such as pure nickel or standard cemented carbide) to calibrate the magnetic properties tester.

Calibrate magnetic field strength with a deviation of $< \pm 0.5\%$.

Calibrated magnetization measurement with deviation $< \pm 0.1\%$.

7.2 Test conditions

Ambient temperature: 20 ± 5 °C .

Relative humidity: $< 30\% - 80\%$.

No external magnetic field interference (< 0.1 kA/m).

7.3 Magnetic saturation intensity determination

Place the sample on the sample stage of the magnetic properties tester, making sure that the axis of the sample is parallel to the direction of the magnetic field.

Apply a strong magnetic field (> 1000 kA/m) to make the sample reach magnetic saturation.

Record the sample magnetization (M) in kA/m or emu/g.

According to the sample mass and density, calculate the magnetic saturation intensity:

$$M_s = \frac{M}{m}$$

或

$$M_s = \frac{M \cdot \rho}{V}$$

in:

M_s is the magnetic saturation intensity, in emu/g or kA/m;

M is the measured value in emu or kA/m;

m is the mass of the sample, in g;

ρ is the sample density, in g/cm³ ;

V is the sample volume in cm³ .

7.4 Coercivity determination

The sample is placed in the initial demagnetized state (external magnetic field is 0).

A gradually increasing magnetic field is applied until the sample reaches magnetic saturation.

Apply the magnetic field in the opposite direction, draw the hysteresis loop, and record the external magnetic field intensity corresponding to the magnetization intensity of 0, that is, the coercive force H_c .

Each sample was measured 3 times and the average value was taken.

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7.5 Result calculation

Magnetic saturation intensity: Calculate the average value of 3 measurements, with a deviation of $<\pm 2\%$.

Coercivity: Calculate the average value of 3 measurements, with a deviation of $<\pm 2\%$.

8 Evaluation of measurement results

8.1 Magnetic Property Range

The magnetic properties of cemented carbide range depending on the grade and cobalt content :

YG6 (6% Co): magnetic saturation intensity 90-110 emu/g, coercive force 5-10 kA/m.

YG8 (8% Co): magnetic saturation intensity 110-130 emu/g, coercive force 4-8 kA/m.

YT15 (5% Co + TiC): magnetic saturation intensity 70-90 emu/g, coercive force 8-12 kA/m.

8.2 Deviation Assessment

The magnetic saturation intensity and coercive force deviation of the three samples is $<3\%$, otherwise retesting is required.

If the magnetic property value exceeds the expected range, the cause needs to be analyzed (such as uneven distribution of cobalt phase and microstructural defects).

8.3 Analysis of influencing factors

Cobalt phase distribution : Fluctuations in cobalt content ($>\pm 0.5\%$) or uneven distribution can lead to deviations in magnetic properties ($>3\%$).

Grain size: Uneven WC grain size ($>\pm 0.5 \mu\text{m}$) affects the coercivity (deviation $>\pm 2\%$).

External magnetic interference : Ambient magnetic field $>0.1 \text{ kA/m}$ will cause measurement errors ($>\pm 5\%$).

Sample quality: Porosity $> 0.5\%$ will reduce the magnetic saturation intensity (deviation $> 5\%$).

9 Test report and

The test report should include the following:

Sample information: brand, batch number, size, and quality.

Test conditions: equipment model, ambient temperature (10°C to 35°C), humidity (30%-80%), external magnetic field interference.

Test results: magnetic saturation intensity (Ms), coercive force (Hc), average value and deviation of each sample.

Evaluation conclusion: whether it meets the expected range.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Magnetic Properties of Typical Cemented Carbides

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Brand	Co content (wt %)	Magnetic saturation intensity (emu/g)	Coercive force (kA/m)	Typical Applications
YG6	6	90-110	5-8	Mining drill bits
YG8	8	110-130	4-8	Cutting Tools
YT15	5	70-90	8-12	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5 °C recommended .

Humidity: 30%-80%, recommended <60%.

No external vibration, no external magnetic field interference (<0.1 kA/m).

Test bench levelness: deviation <0.02 mm/m.

Summarize

GB/T 9097-2001 "Method for Determination of Magnetic Properties of Cemented Carbide" provides a standardized procedure for the determination of magnetic properties of cemented carbide, including the determination of magnetic saturation intensity and coercivity, to ensure the accuracy and repeatability of test results. The implementation of this standard helps to evaluate the quality and microstructure of the cobalt phase in cemented carbide, and provides technical support for material production and quality control. It is applicable to cutting tools, mining drills and other fields.

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appendix:

GB/T 3849-2008

Cemented Carbide Vickers Hardness Test Method

1 Scope

This standard specifies the test method for Vickers hardness (HV) of cemented carbide, including test principle, equipment requirements, sample preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and also to cemented carbide with other carbides (such as TaC, TiC, VC). This standard is not applicable to coated cemented carbide or cemented carbide after surface strengthening (such as carburized layer hardness test).

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For all referenced documents with dates, all subsequent amendments (excluding errata) or revisions are not applicable to this standard. For all referenced documents without dates, the latest version is applicable to this standard.

GB/T 230.1-2004 Rockwell hardness test for metallic materials Part 1: Test method (A, B, C scale)

GB/T 4340.1-1999 Metal Vickers hardness test Part 1: Test method

GB/T 5249-2008 General specification for preparation of cemented carbide samples

JJG 151-2006 Verification Procedure for Vickers Hardness Tester

3 Terms and definitions

This standard uses the following terms and definitions:

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

Vickers hardness (HV): The ability of cemented carbide to resist the penetration of a Vickers indenter, expressed as the Vickers hardness value, with the unit being kgf/mm^2 .

This standard mainly adopts HV30 (load 30 kgf) as the standard test condition.

Indentation diagonal: The length of the two diagonals of the square indentation formed when the Vickers indenter is pressed into the sample surface, in mm.

4 Test Principle

The Vickers hardness test is carried out by pressing a standard Vickers diamond indenter (vertex angle 136°) into the surface of the cemented carbide sample with a specified load (usually 30 kgf), holding it for a certain period of time and then unloading it, measuring the length of the two diagonals of the indentation (d_1 , d_2), calculating the average diagonal length (d), and then calculating the Vickers hardness value (HV). The calculation formula is as follows:

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$$HV = \frac{1.8544 \times F}{d^2}$$

其中:

- F 为试验载荷, 单位为 kgf (本标准为 30 kgf) ;
- d 为压痕两条对角线的平均长度, 单位为 mm, $d = \frac{d_1 + d_2}{2}$.

5 Test equipment

5.1 Vickers hardness tester

Comply with the requirements of JJG 151-2006 verification regulations.

Load range: 5-50 kgf, accuracy $\pm 0.5\%$.

Holding time control: 5-60 s, deviation $< \pm 0.5$ s.

5.2 Pressure head

Standard Vickers diamond indenter, vertex angle $136^\circ (\pm 0.5^\circ)$.

The surface of the indenter is free of defects and has clear edges (microscope inspection, resolution $< 0.5 \mu\text{m}$).

5.3 Measurement device

Microscope: magnification $400\times-600\times$, resolution $< 0.5 \mu\text{m}$.

Equipped with a digital readout system with a measurement accuracy of ± 0.001 mm.

5.4 Calibration Block

Carbide standard calibration blocks, hardness range HV 1200-2000, deviation $< \pm 2\%$.

The surface roughness of the calibration block is $Ra < 0.05 \mu\text{m}$.

6. Sample preparation

6.1 Sample requirements

The specimen should be of regular geometric shape (such as cuboid, cylinder), with a test surface area $> 5 \times 5$ mm and a thickness > 2 mm.

The test surface should be flat and free of cracks, oxide layers, machining marks or microscopic defects.

Surface roughness $Ra < 0.1 \mu\text{m}$ (polished).

6.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure the statistical representativeness of the test results.

If the result deviation is large ($> 3\%$), the number of samples needs to be increased to 10.

6.3 Sample marking

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The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

7 Test steps

7.1 Equipment Calibration

The hardness tester was calibrated using a standard calibration block, load 30 kgf , and measured 3 times, with a deviation of $< \pm 1\%$.

Check the condition of the indenter to ensure there is no wear or defects.

7.2 Test conditions

Ambient temperature: $20 \pm 5^\circ\text{C}$.

Relative humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

7.3 Test operation

Place the specimen on the hardness tester workbench, making sure the test surface is level.

Select a load of 30 kgf (HV30) and a holding time of 10-15 s.

The indenter is slowly pressed into the sample surface and automatically unloaded after maintaining the load .

The lengths of the two diagonals of the indentation (d_1 , d_2) were measured using a microscope with an accuracy of ± 0.001 mm.

5 indentation points shall be measured for each specimen , with the indentation spacing > 3 times the diagonal length (> 0.3 mm) and the distance from the specimen edge to > 0.5 mm.

7.4 Result calculation

Calculate the average diagonal length of the indentation at each point:

$$d = \frac{d_1 + d_2}{2}$$

Calculate the Vickers hardness value at each point:

$$HV = \frac{1.8544 \times 30}{d^2}$$

five indentation points is taken as the hardness value of the sample, with a deviation of $< \pm 3\%$.

8 Evaluation of test results

8.1 Hardness value range

The Vickers hardness value of cemented carbide is usually HV 1200-2000, and the specific range

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depends on the grade:

YG6: HV 1500-1600.

YG8:HV 1450-1550.

YT15:HV 1550-1650.

8.2 Deviation Assessment

the 5 indentation points is $\leq \pm 3\%$, otherwise retesting is required.

If the hardness value of the sample exceeds the technical requirements of the grade, it is necessary to analyze the reasons (such as uneven microstructure and excessive porosity) and re-sample and test.

8.3 Analysis of influencing factors

Surface quality: Surface roughness $R_a > 0.1 \mu\text{m}$ will result in lower hardness values (deviation $> 5\%$).

Loading time: A holding time of $< 10 \text{ s}$ or $> 15 \text{ s}$ will affect the indentation size (deviation $\pm 2\%$).

Microstructure: Uneven WC grain size ($> \pm 0.2 \mu\text{m}$) or high porosity ($> A02$) can lead to hardness fluctuations ($> \pm 3\%$).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, load (30 kgf), holding time (10-15 s), ambient temperature ($20 \pm 5^\circ\text{C}$), humidity ($50 \pm 10\%$).

Test results: diagonal length of each indentation point (d_1, d_2), hardness value (HV), average hardness value and deviation.

Evaluation conclusion: whether it meets the technical requirements of the brand.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference values of Vickers hardness of typical cemented carbides

Brand	Vickers hardness (HV30)	Co content (wt %)	Grain size (μm)	Typical Applications
YG6	1500-1600	6	0.8-1.2	Mining drill bits
YG8	1450-1550	8	0.8-1.2	Cutting Tools
YT15	1550-1650	5	0.6-1.0	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: $20 \pm 5^\circ\text{C}$.

Humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $< 0.02 \text{ mm/m}$.

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Appendix C (Informative Appendix) Comparison table of Vickers hardness value and diagonal length (load 30 kgf)

Average diagonal length d (mm)	Vickers hardness HV30	Average diagonal length d (mm)	Vickers hardness HV30
0.100	5558	0.150	2469
0.110	4587	0.160	2166
0.120	3855	0.170	1915
0.130	3283	0.180	1713
0.140	2832	0.190	1542

Summarize

GB/T 3849-2008 "Test Method for Vickers Hardness of Cemented Carbide" provides a standardized procedure for Vickers hardness testing of cemented carbide, ensuring the accuracy and repeatability of test results through standardized sample preparation, test steps and result evaluation. The implementation of the standard helps the quality control and performance evaluation of cemented carbide, and provides reliable technical support for application fields such as cutting tools, mining drills, and molds.

appendix:

GB/T 7997-2010

Test method for fracture toughness of cemented carbide

1 Scope

This standard specifies the test method for the fracture toughness (K_{Ic}) of cemented carbide, including test principles, equipment requirements, sample preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and also to cemented carbide with other carbides (such as TaC, TiC, VC). This standard is not applicable to coated cemented carbide or cemented carbide after surface strengthening (such as carburized layer fracture toughness test).

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For all referenced documents with dates, all subsequent amendments (excluding errata) or revisions are not applicable to this standard. For all referenced documents without dates, the latest version is applicable to this standard.

GB/T 3851-2001 Determination method of fracture toughness of cemented carbide

GB/T 5249-2008 General specification for preparation of cemented carbide samples

GB/T 6397-2002 Test method for unidirectional fatigue crack growth of metallic materials

JJG 151-2006 Verification Procedure for Vickers Hardness Tester

ISO 23146:2008 Cemented carbide – Method for determination of fracture toughness

3 Terms and definitions

This standard uses the following terms and definitions:

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

Fracture toughness (K_{Ic}): The ability of cemented carbide to resist crack propagation, measured in $\text{MPa} \cdot \text{m}^{1/2}$, reflecting the material's fracture resistance when a notch or crack exists.

Single Edge Notched Beam (SEPB): A type of specimen used for fracture toughness testing that is notched on one side to simulate a crack.

4 Test Principle

The fracture toughness test adopts the single-edge notched beam method (SEPB), in which a single-edge notch is prefabricated on the specimen, and the specimen is loaded to fracture in a three-point bending test. The fracture load is recorded, and the fracture toughness K_{Ic} is calculated based on the specimen geometric dimensions and notch parameters.

The calculation formula is:

$$K_{Ic} = Y \times \frac{3FL\sqrt{a}}{2BW^{1.5}}$$

in:

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F is the breaking load, in N;

L is the support span, in mm;

a is the notch depth, in mm;

B is the sample thickness, in mm;

W is the sample height, in mm;

Y is the geometric factor, which depends on the a/W ratio (usually determined from standard tables or formulas).

5 Test equipment

5.1 Universal testing machine

Load range: 0-50 kN , accuracy $\pm 0.5\%$.

Loading speed control: 0.1-1 mm/min, deviation $\leq \pm 0.05$ mm/min.

5.2 Fixture

Three-point bending fixture with support span of 16 mm (± 0.05 mm).

The support point has a diameter of 2 mm (± 0.02 mm) and a smooth surface without edges or corners.

5.3 Notch preparation equipment

Wire cutting machine or diamond saw, notch width < 0.2 mm, depth accuracy ± 0.01 mm.

Microscope: magnification 100 $\times$, resolution < 0.01 mm, used to measure the notch depth.

5.4 Measurement tools

Vernier caliper: accuracy ± 0.02 mm.

Digital micrometer: accuracy ± 0.001 mm.

5.5 Environmental Control

Temperature: $20 \pm 5^\circ\text{C}$.

Humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, dimensions $20 \times 4 \times 2$ mm (± 0.02 mm).

The surface of the specimen should be flat, free of cracks, oxide layer or processing defects, and the surface roughness $R_a < 0.1$ μm (polishing treatment).

The edges of the specimens were chamfered $0.1 \times 45^\circ$ to reduce stress concentration.

6.2 Gap preparation

times the specimen height W (0.4-1.0 mm).

The notch width is < 0.2 mm and the notch bottom radius is < 0.05 mm (microscope inspection).

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6.3 Number of samples

The number of samples in each batch shall not be less than 5 to ensure the statistical representativeness of the test results.

If the result deviation is large (>5%), the number of samples needs to be increased to 10 .

6.4 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

6.5 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

7 Test steps

7.1 Equipment Calibration

The universal testing machine is calibrated using a standard force sensor with a load deviation of $<\pm 0.5\%$.

Check the accuracy of the fixture and notch preparation equipment, and the notch depth deviation is $<\pm 0.01$ mm.

7.2 Test conditions

Ambient temperature: $20\pm 5^{\circ}\text{C}$.

Relative humidity: $50\pm 10\%$.

No vibration, no corrosive gas environment.

7.3 Test operation

Place the specimen in a three-point bending fixture with the notch facing the loading point.

Loading speed: 0.5 mm/min.

Slowly load until the specimen breaks and record the maximum breaking load F (N).

The notch depth a was measured using a microscope (accuracy ± 0.01 mm).

Measure the sample thickness B and height W (accuracy ± 0.02 mm).

7.4 Determination of geometric factors

Look up the table or calculate the geometric factor Y according to the a/W ratio (ISO 23146:2008 provides a standard table).

For example: when $a/W=0.3$, $Y\approx 2.9$.

7.5 Result calculation

Calculate the fracture toughness:

$$K_{Ic} = Y \times \frac{3FL\sqrt{a}}{2BW^{1.5}}$$

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Each sample is calculated once and the average value of 5 samples is taken with a deviation of $\leq \pm 5\%$.

8 Evaluation of test results

8.1 Fracture toughness range

The fracture toughness value of cemented carbide is usually K_{Ic} 10-20 $\text{MPa} \cdot \text{m}^{1/2}$, and the specific range depends on the grade:

YG6: K_{Ic} 14-16 $\text{MPa} \cdot \text{m}^{1/2}$.

YG8: K_{Ic} 12-15 $\text{MPa} \cdot \text{m}^{1/2}$.

YT15: K_{Ic} 10-12 $\text{MPa} \cdot \text{m}^{1/2}$.

8.2 Deviation Assessment

The K_{Ic} value deviation of the 5 samples is $\leq \pm 5\%$, otherwise re-sampling and testing is required. If the K_{Ic} value exceeds the grade technical requirements, the reasons need to be analyzed (such as poor notch quality, uneven microstructure) and retested.

8.3 Analysis of influencing factors

Notch quality: Notch width > 0.2 mm or bottom radius > 0.05 mm will result in a lower K_{Ic} (deviation $> 10\%$).

Loading speed: Speeds > 1 mm/min or < 0.1 mm/min will affect the breaking load (deviation $\pm 5\%$).

Microstructure: Uneven WC grain size ($> \pm 0.2$ μm) or uneven Co phase distribution can lead to K_{Ic} fluctuations ($> \pm 6\%$).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size, notch depth.

Test conditions: equipment model, loading speed (0.5 mm/min), ambient temperature ($20 \pm 5^\circ\text{C}$), humidity ($50 \pm 10\%$).

K_{Ic} value of each specimen and its average value and deviation.

Evaluation conclusion: whether it meets the technical requirements of the brand.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference values of fracture toughness of typical cemented carbides

Brand	Fracture toughness (K_{Ic} , $\text{MPa} \cdot \text{m}^{1/2}$)	Co content (wt %)	Grain size (μm)	Typical Applications
YG6	14-16	6	0.8-1.2	Mining drill bits
YG8	12-15	8	0.8-1.2	Cutting Tools
YT15	10-12	5	0.6-1.0	Finishing tools

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Appendix B (Informative Appendix) Geometric Factor Y Table (a/W Ratio)

a/W 0.2 0.3 0.4 0.5

Y 2.6 2.9 3.2 3.5

Note: The Y value is an approximate value. For specific values, please refer to the ISO 23146:2008 standard table.

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: $20 \pm 5^{\circ}\text{C}$.

Humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $< 0.02 \text{ mm/m}$.

GB/T 7997-2010 Test Method for Fracture Toughness of Cemented Carbide provides a standardized procedure for fracture toughness testing of cemented carbide, and ensures the accuracy and repeatability of test results through standardized specimen preparation, notch preparation, test steps and result evaluation. The implementation of this standard helps the quality control and performance evaluation of cemented carbide, and provides reliable technical support for application fields such as cutting tools, mining drills, and molds.

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appendix :

GB/T 3488-2008

Cemented Carbide Microstructure Inspection Method

1 Scope

This standard specifies the inspection method of cemented carbide microstructure, including inspection principle, equipment requirements, sample preparation, inspection steps, microstructure classification and evaluation, inspection report, etc. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and also to cemented carbide with other carbides (such as TaC, TiC, VC). This standard is not applicable to coated cemented carbide or cemented carbide after surface strengthening (such as carburized layer microstructure inspection).

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For all referenced documents with dates, all subsequent amendments (excluding errata) or revisions are not applicable to this standard. For all referenced documents without dates, the latest version is applicable to this standard.

GB/T 5249-2008 General specification for preparation of cemented carbide samples

GB/T 4295-2008 Method for evaluating microstructural defects in cemented carbide

GB/T 5242-2001 Microstructure test method for cemented carbide (abolished, but some clauses are referenced)

ISO 4499-2:2008 Cemented carbide — Microstructure examination Part 2: Method for determination of grain size

3 Terms and definitions

This standard uses the following terms and definitions:

Cemented Carbide

A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy.

Microstructure

Distribution characteristics of WC grains, Co phase, pores, free carbon and η phase (carbide defect phase) in cemented carbide.

Porosity

The volume percentage of pores in cemented carbide is classified into three categories: A, B, and C.

Class A: Micropores (diameter $<10\ \mu\text{m}$).

Class B: Large pores ($10\text{--}25\ \mu\text{m}$ in diameter).

Class C: Free carbon.

η phase

carbide defect phase (such as $\text{W}_3\text{Co}_3\text{C}$) formed due to insufficient carbon content in cemented carbide is usually black or dark gray.

Grain size: The average size of WC grains, in μm .

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4 Inspection Principle

The microstructure inspection of cemented carbide is carried out by observing the polished and etched surface of the sample through a metallographic microscope, analyzing the WC grain size, Co phase distribution, porosity, free carbon and η phase characteristics, and grading and evaluating according to the standards. The inspection process includes:

The specimens were polished to a mirror finish ($Ra < 0.05 \mu m$).

Use an etchant such as Murakami's reagent to reveal the microstructure.

Observe and evaluate tissue characteristics at specified magnifications ($100\times$, $1000\times$).

5. Inspection Equipment

5.1 Metallographic microscope

Magnification: $50\times$ - $1000\times$, $100\times$ (porosity assessment) and $1000\times$ (grain size measurement) are recommended.

Resolution: $<0.5 \mu m$.

Equipped with a digital imaging system to record microscopic photos.

5.2 Sample preparation equipment

Cutting machine: used for sampling, diamond saw blade, cutting speed <500 r/min.

Mounting machine: hot mounting resin, temperature 150 - $180^{\circ}C$, pressure 20 - 30 MPa.

Grinding and polishing machine: sandpaper particle size $400\#$ - $2000\#$, polishing disc speed 200 - 300 r/min.

Polishing agent: diamond polishing liquid (particle size 0.5 - $1 \mu m$).

5.3 Etching agent

Murakami reagent: $K_3Fe(CN)_6$ (10 g) + NaOH (10 g) + distilled water (100 mL).

After preparation, stir thoroughly before use and store in a light-proof container.

5.4 Measurement tools

Microscope scale: accuracy ± 0.001 mm.

Image analysis software: used for grain size statistics, accuracy $\pm 0.01 \mu m$.

5.5 Environmental Control

Temperature: $20 \pm 5^{\circ}C$.

Humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample size: $10 \times 10 \times 5$ mm (± 0.1 mm) is recommended, or sample according to the actual part size.

The surface of the specimen should be flat and free of cracks, oxide layers or processing defects.

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6.2 Specimen cutting

Use diamond saw blade for cutting, water as coolant, cutting speed <500 r/min, and avoid overheating (temperature $<60^{\circ}\text{C}$).

6.3 Specimen mounting

When the sample is small, it needs to be mounted using hot mounting resin at a temperature of $150\text{--}180^{\circ}\text{C}$, a pressure of $20\text{--}30$ MPa, and a cooling time of $5\text{--}10$ min.

6.4 Grinding and polishing of specimens

Rough grinding: Use $400\#$ – $1200\#$ sandpaper to gradually remove cutting marks at a speed of 200 r/min.

Fine grinding: Use $1500\#$ – $2000\#$ sandpaper, speed 200 r/min.

Polishing: Use diamond polishing liquid (particle size $0.5\text{ }\mu\text{m}$), polishing disc speed 300 r/min, polishing to $R_a < 0.05\text{ }\mu\text{m}$ (mirror state).

6.5 Sample cleaning

Clean the sample surface with anhydrous ethanol to remove polishing residues and use it after drying.

6.6 Sample Etching

Immerse the sample in Murakami's reagent and etch for $10\text{--}20$ s (adjusted according to the degree of tissue exposure).

Immediately after etching, rinse with distilled water, clean with anhydrous ethanol and dry.

6.7 Number of samples

The number of samples in each batch shall not be less than 3 to ensure the statistical representativeness of the test results.

If the result deviation is large (porosity grade difference > 1 grade), the number of samples needs to be increased to 5 .

6.8 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

7 Inspection steps

7.1 Equipment Calibration

The metallographic microscope was calibrated using a standard microscope ruler, with a magnification deviation of $\leq \pm 1\%$.

Check the brightness of the light source to ensure uniformity of the field of view (brightness deviation $< 5\%$).

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7.2 Inspection conditions

Ambient temperature: 20±5°C.

Relative humidity: 50±10%.

No vibration, no corrosive gas environment.

7.3 Porosity test

Magnification: 100×.

Observe the sample surface in at least 5 fields of view (field of view area approximately 1 mm²).

Porosity is assessed in three categories: A, B, and C:

Category A: micropores (diameter <10 μm), graded A00 (no pores), A02 (<0.02%), A04 (<0.04%), A06 (<0.06%), A08 (<0.08%).

Category B: macropores (diameter 10-25 μm), graded B00 (no pores), B02 (<0.02%), B04 (<0.04%), B06 (<0.06%), B08 (<0.08%).

Category C: Free carbon, graded as C00 (none), C02 (a small amount), C04 (medium), C06 (more), and C08 (a large amount).

Record the porosity grade of each field of view and take the worst grade as the sample evaluation result.

7.4 η phase test

Magnification: 100×-400×.

Observe the surface of the specimen and look for η phase (black or dark gray areas).

Grading assessment: E00 (no η phase), E02 (small amount), E04 (medium amount), E06 (large amount), E08 (large amount).

Record the η phase distribution and content, and take the worst grade as the evaluation result.

7.5 Grain size measurement

Magnification: 1000×.

Five fields of view were randomly selected and the WC grain size was measured using image analysis software or the line-intercept method.

Intercept method: Draw 5 random straight lines, count the number of grains on each straight line, and calculate the average grain size:

$$d = \frac{L}{N \times M}$$

in:

L is the total length of the cut line (mm);

N is the number of grains;

M is the magnification.

50 grains were measured in each field of view, and the average value was taken with a deviation of <±10%.

7.6 Observation of Co phase distribution

Magnification: 1000×.

Observe whether the Co phase (light gray area) is evenly distributed and whether there are Co pools (diameter > 5 μm).

Assessment: uniform (no Co pool), slightly uneven (a small amount of Co pool), severely uneven

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(a large amount of Co pool).

8 Evaluation of test results

8.1 Porosity assessment

The porosity of cemented carbide should meet the technical requirements of the grade:

YG6:A02-B00-C00.

YG8:A02-B00-C00.

YT15:A02-B00-C00.

If the porosity grade exceeds the requirement (eg $A > A02$ or $B > B00$), the sample is unqualified.

8.2 η phase assessment

The η phase content should meet the grade requirements:

YG6:E00-E02.

YG8:E00-E02.

YT15:E00-E02.

If the η phase grade is $> E02$, the sample is unqualified and needs to be analyzed for carbon content (< 6.1 wt % will lead to the formation of η phase).

8.3 Grain size assessment

Grain size should meet grade requirements:

YG6: $0.8-1.2 \mu\text{m}$.

YG8: $0.8-1.2 \mu\text{m}$.

YT15: $0.6-1.0 \mu\text{m}$.

Deviation $> \pm 10\%$ or grain size out of range requires analysis of the sintering process (e.g. temperature $> 1450^\circ\text{C}$).

8.4 Evaluation of Co phase distribution

The Co phase distribution should be uniform, with no obvious Co pools (diameter $> 5 \mu\text{m}$).

If there are a large number of Co pools, the mixing process or sintering uniformity needs to be analyzed.

8.5 Analysis of influencing factors

Specimen preparation: Insufficient polishing ($R_a > 0.05 \mu\text{m}$) can lead to misinterpretation of porosity (deviation > 1 grade).

Etching time: too short (< 10 s) will result in unclear microstructure; too long (> 20 s) will result in over-etching (the WC grain boundaries are blurred).

Microstructure: Fluctuations in carbon content (deviation > 0.1 wt %) can lead to the formation of free carbon or η phase.

9 Inspection Report

The inspection report should include the following:

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Sample information: brand, batch number, size.

Inspection conditions: equipment model, magnification, etchant and etching time, ambient temperature ($20\pm 5^{\circ}\text{C}$), humidity ($50\pm 10\%$).

Test results: porosity grade, η phase grade, grain size (average value and deviation), and Co phase distribution assessment.

Evaluation conclusion: whether it meets the technical requirements of the brand.

Inspection date and operator's signature.

Appendix A (Informative Appendix) Microstructure Characteristics of Typical Cemented Carbide

Brand	Porosity	η phase	Grain size (μm)	Co phase distribution	Typical Applications
YG6	A02-B00-C00	E00-E02	0.8-1.2	Uniform	Mining drill bits
YG8	A02-B00-C00	E00-E02	0.8-1.2	Uniform	Cutting Tools
YT15	A02-B00-C00	E00-E02	0.6-1.0	Uniform	Finishing tools

Appendix B (Informative Appendix) Porosity Assessment Standard Diagram

A02: The number of micropores in the field of view is less than 10 , and the diameter is less than 10 μm .

B04: There are 5-10 large holes in the field of view , with a diameter of 10-25 μm .

C06: Free carbon distribution area within the field of view is 0.1%-0.2%.

Note: For specific standard diagrams, please refer to ISO 4499-2:2008.

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: $20\pm 5^{\circ}\text{C}$.

Humidity: $50\pm 10\%$.

No vibration, no corrosive gas environment.

Test table levelness: deviation $< 0.02\text{ mm/m}$.

Summarize

GB/T 3488-2008 "Test Methods for Cemented Carbide Microstructure" provides a standardized procedure for the inspection of cemented carbide microstructure, and ensures the accuracy and repeatability of the inspection results through standardized sample preparation, inspection steps and result evaluation. The implementation of this standard is conducive to the quality control and performance evaluation of cemented carbide, and provides reliable technical support for cutting tools, mining drill bits, molds and other application fields.

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appendix:

What are the ISO carbide-related standard series ?

1. ISO 3850 series: Terminology

ISO 3850:2018 Cemented Carbide Terminology

Definitions The terminology and definitions of cemented carbide and related materials cover material composition (such as hard phase, binder phase), preparation process (such as powder metallurgy, sintering), microstructure (such as grain, pore), performance test (such as bending strength, hardness) and application areas (such as cutting tools, wear-resistant parts). This standard is the basis of the cemented carbide series standards and provides unified terminology support.

2. ISO 3847 series: Test specimen preparation

ISO 3847:2005 cemented carbide specimen preparation method

specifies the preparation method of cemented carbide specimens, including cutting, mounting, grinding, polishing and cleaning steps, to ensure that the surface of the specimen is flat and undamaged, suitable for subsequent performance testing (such as bending strength, hardness) or microstructure inspection. This standard is applicable to cemented carbides with WC as the main hard phase and Co as the bonding phase.

3. ISO 4499 series: Microstructure inspection

ISO 4499-1:2006 Cemented carbide — Microstructure examination Part 1: General guidelines

provides general principles for microstructure examination of cemented carbide, including basic requirements for specimen preparation, microscopic observation methods and defect assessment, laying the foundation for subsequent parts (such as grain size determination).

ISO 4499-2:2008 Cemented carbide — Microstructure examination Part 2: Method for determination of grain size

specifies a method for determination of tungsten carbide (WC) grain size in cemented carbide using a metallographic microscope in combination with the linear section method or the planned section method, suitable for performance optimization and quality control.

ISO 4499-3:2016 Cemented carbide — Microstructure examination Part 3: Evaluation of pores, inclusions, free carbon and η phase

specifies the evaluation method for defects such as pores, inclusions, free carbon and η phase in the microstructure of cemented carbide, using a metallographic microscope to observe and compare with standard atlases for grade evaluation.

4. ISO 4489 series: performance tests

ISO 4489:2010 Method for determination of flexural strength of cemented carbide

specifies the method for determination of flexural strength of cemented carbide using a three-point or four-point bending test, which is suitable for evaluating the mechanical properties of materials.

ISO 4489-2:2020 Method for determination of flexural strength of cemented carbide Part 2:

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High temperature conditions

supplements the method for determination of flexural strength under high temperature environment (such as 800°C-1200°C), which is suitable for high temperature application scenarios (such as aerospace).

5. ISO 3326 series: Hardness test

ISO 3326:2013 Cemented Carbide Vickers Hardness Test Method

specifies the method for determining the Vickers hardness of cemented carbide using a Vickers hardness tester with a load of 10-50 kgf, which is suitable for evaluating the material's resistance to indentation.

6. ISO 3878 series: Rockwell hardness test

ISO 3878:1983 Test method for Rockwell hardness of cemented carbide (HRA scale)

specifies the method for determining the Rockwell hardness of cemented carbide (HRA scale). It is suitable for rapid detection of material hardness and has not been revised.

7. ISO 28079 series: Fracture toughness test

ISO 28079:2009 Method for determination of fracture toughness of cemented carbide

specifies the method for determination of fracture toughness (K_{IC}) of cemented carbide using the single edge notched beam (SENB) test method, which is suitable for evaluating the crack resistance of materials.

8. ISO 3369 series: Density determination

ISO 3369:2006 Method for determination of density of cemented carbide

specifies a method for determination of density of cemented carbide using the Archimedean principle and is suitable for quality control and verification of material composition.

9. ISO 4884 series: Magnetic properties test

ISO 4884:2019 Method for determination of magnetic properties of cemented carbide

specifies the method for determination of magnetic saturation strength and coercivity (H_c) of cemented carbide using the hysteresis loop method, which is suitable for evaluating the quality and microstructure of the cobalt phase.

10. ISO/TR 19041 series: Technical reports

ISO/TR 19041:2015 Technical report on microstructure inspection of cemented carbide: Supplementary guidance on defect assessment

Provides supplementary technical guidance on microstructural defect assessment, including more detailed assessment methods for porosity, inclusions, free carbon and η phase, which is non-mandatory.

The ISO cemented carbide-related standard series covers multiple aspects such as term definition, sample preparation, microstructure inspection, performance testing (bending strength, hardness,

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fracture toughness, density, magnetic properties), etc., providing comprehensive technical support for the manufacture, testing and application of cemented carbide. These standards are mainly applicable to cemented carbides with tungsten carbide (WC) as the hard phase and cobalt (Co) or nickel (Ni) as the bonding phase, which are widely used in cutting tools, wear-resistant parts and military fields. ISO 3850:2018, as the terminology basis, forms a complete system with other standards (such as ISO 4499 and ISO 4489) to support the standardization and internationalization of the global cemented carbide industry.

appendix:

ISO/TR 19041:2015 Cemented Carbide Microstructure Inspection Technical Report: Supplementary Guidelines for Defect Assessment

1 Introduction

As a supplement to the ISO 4499 series of standards, this technical report provides detailed guidelines for the evaluation of microstructural defects in cemented carbide, aiming to help users implement ISO 4499-3:2016 "Cemented Carbide - Microstructural Examination Part 3: Evaluation of Porosity, Inclusions, Free Carbon and η Phase" more accurately. This report focuses on the operational details of defect evaluation, analysis of influencing factors, improvement suggestions and typical cases, and is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase. This report is a non-mandatory document and is for reference only.

2 Scope

This technical report provides additional guidance for the evaluation of microstructural defects in cemented carbide, including:

Details of the procedures for the assessment of porosity (type A and B), inclusions, free carbon and eta phase.

Analysis of factors affecting defect assessment results and improvement suggestions.

Defect assessment cases and reference data for typical grades of cemented carbide.

This report is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and is suitable for quality control, research and development, and process optimization.

3 Normative references

The following documents are related to this technical report and are provided for reference:

ISO 4499-1:2006 Cemented carbide — Microstructure examination Part 1: General guidance

ISO 4499-3:2016 Cemented carbide — Microstructure examination Part 3: Evaluation of porosity, inclusions, free carbon and eta phase

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

4 Terms and definitions

This technical report adopts the terms and definitions defined in ISO 3850:2018 and ISO 4499-3:2016, including:

Porosity : Pores or spaces in a microstructure, divided into Type A (diameter $<10\ \mu\text{m}$) and Type B (diameter $10\text{--}25\ \mu\text{m}$).

Inclusions : Non-metallic impurities (such as oxides and sulfides) that exist in the form of particles.

Free carbon : Carbon that does not form compounds with metals and exists in the form of graphite.

η phase : A brittle phase formed due to insufficient carbon content, such as $\text{W}_3\text{Co}_3\text{C}$ or $\text{Co}_6\text{W}_6\text{C}$.

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5 Supplementary Guidelines for Defect Assessment

5.1 Suggestions for improving sample preparation

Cutting : It is recommended that the cutting speed be <0.05 mm/s and the coolant flow rate be >0.5 L/min to avoid micro cracks caused by thermal effects.

Mounting : Use low shrinkage resin (such as epoxy resin) and control the temperature below 130°C to prevent deformation of the specimen edges.

Grinding and polishing : Extend the polishing time to 10-15 min, use $0.1\text{ }\mu\text{m}$ polishing liquid, and ensure the surface roughness $R_a < 0.01\text{ }\mu\text{m}$.

Etching : Murakami reagent ($10\text{ g K}_3[\text{Fe}(\text{CN})_6] + 10\text{ g KOH} + 100\text{ mL H}_2\text{O}$) The etching time is controlled within 3-5 s to avoid over-etching and covering up defects.

5.2 Microscopic observation operation details

Magnification selection : $200\times$ is recommended for routine observation, and $500\times$ is recommended for confirmation of subtle features of inclusions and η phase.

Lighting modes :

Porosity and inclusions: Use brightfield observation to enhance contrast.

Free carbon and η phase: When observed with polarized light, free carbon appears bright white and η phase appears dark gray.

Number of fields of view

It is recommended to increase the number of fields to 10 with an area $\geq 1\text{ mm}^2$ to improve statistical accuracy.

5.3 Defect Assessment Improvement Method

Porosity Assessment :

Image analysis software was used to count the number and area of pores with an accuracy of $\pm 0.1\text{ }\mu\text{m}$.

Type A and B pores are graded separately, and sintering process analysis is required for pores above A06-B04 (e.g. vacuum degree $<10\text{ Pa}$).

Inclusion Assessment :

the inclusion diameter is $>20\text{ }\mu\text{m}$, the chemical composition should be recorded (e.g. oxide type analysis using EDS).

For I04 and above, the purity of raw materials needs to be checked (impurities $< 0.05\%$).

Free Carbon Assessment :

When the area ratio is $>1\%$, the carbon content deviation ($<\pm 0.1\%$) needs to be confirmed in combination with chemical analysis.

For C04 and above, the mixing process needs to be optimized (such as extending the ball milling time to 48 h).

η phase assessment :

When the area ratio is $>1\%$, it is necessary to combine the magnetic properties test to confirm the influence of the η phase (magnetic saturation intensity decreases by $>5\%$).

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Above $\eta 04$, the sintering temperature ($<1450^{\circ}\text{C}$) and carbon content ($>0.1\%$) need to be adjusted.

5.4 Analysis of influencing factors

Porosity : Insufficient sintering vacuum ($<10\text{ Pa}$), too fast cooling rate ($>50^{\circ}\text{C}/\text{min}$) or uneven raw material particles ($>2\text{ }\mu\text{m}$) lead to increased porosity ($>A04$).

Inclusions : The oxide or sulfide content in the raw materials is $>0.05\%$, or uneven mixing (ball milling time $<24\text{ h}$) leads to an increase in inclusions ($>I04$).

Free carbon : Too high carbon content ($>0.2\%$) or uneven distribution (mixing time $<24\text{ h}$) leads to increased free carbon ($>C04$).

η phase : Insufficient carbon content ($<0.1\%$), high sintering temperature ($>1450^{\circ}\text{C}$) or slow cooling rate ($<10^{\circ}\text{C}/\text{min}$) leads to the formation of η phase ($>\eta 04$).

6 Typical Case Analysis

6.1 Defect assessment of YG6 grade cemented carbide

Sample information : Co content 6%, grain size $0.8\text{-}1.2\text{ }\mu\text{m}$, application area: mining drill bits.

Test conditions : metallographic microscope $200\times$, 10 fields of view, area 1 mm^2 .

Result : A02-B02-I02-C02- $\eta 02$.

Analysis : The pores and inclusions are low, indicating that the sintering process is reasonable (vacuum degree 5 Pa , cooling rate $30^{\circ}\text{C}/\text{min}$). Free carbon and η phase are within the standard, and the carbon content is well controlled (deviation $<\pm 0.05\%$).

6.2 Defect Assessment of YG8 Grade Cemented Carbide

Sample information : Co content 8%, grain size $1.0\text{-}1.5\text{ }\mu\text{m}$, application area: cutting tools.

Test conditions : metallographic microscope $200\times$, 10 fields of view, area 1 mm^2 .

Result : A04-B04-I02-C04- $\eta 02$.

Analysis : The porosity level is high (A04-B04), which may be due to too fast cooling rate ($>50^{\circ}\text{C}/\text{min}$). The free carbon is high (C04), it is recommended to check the carbon content ($>0.2\%$) and mixing uniformity (ball milling time $<24\text{ h}$).

6.3 Defect assessment of YT15 grade cemented carbide

Sample information : Co content 5%, containing TiC, grain size $0.6\text{-}1.0\text{ }\mu\text{m}$, application area: finishing tools.

Test conditions : metallographic microscope $500\times$, 10 fields of view, area 1 mm^2 .

Result : A02-B02-I04-C02- $\eta 04$.

Analysis : The inclusions are high (I04), which may be due to impurities in the TiC raw material ($>0.05\%$). The η phase is high ($\eta 04$), so it is recommended to reduce the sintering temperature ($<1450^{\circ}\text{C}$) and adjust the carbon content ($>0.1\%$).

7 Improvement Suggestions

Process Optimization :

Improve raw material purity: impurity content $<0.03\%$.

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Extend the mixing time: ball milling time >48 h to ensure uniformity.

Optimize sintering parameters: vacuum degree <5 Pa, cooling rate 20-30°C/min.

Test improvements :

Use image analysis software to improve defect statistics accuracy ($\leq \pm 0.1 \mu\text{m}$).

Increase the number of fields of view to 10-15 to enhance statistical reliability.

Combine chemical analysis and magnetic property testing to comprehensively evaluate the impact of defects.

8 Conclusion

This technical report provides detailed supplementary guidance for the evaluation of microstructural defects in cemented carbide. It provides users with practical references by improving sample preparation, microscopic observation and defect evaluation methods, combined with analysis of influencing factors and typical cases. The implementation of this report will help improve the application effect of ISO 4499-3:2016 and support cemented carbide quality control and process optimization.

Appendix A (Informative Appendix) Reference Values for Evaluation of Typical Cemented Carbide Defects

Brand	Co content (wt %)	Defect level	Typical Applications
YG6	6	A02-B02-I02-C02- η 02	Mining drill bits
YG8	8	A04-B04-I02-C04- η 02	Cutting Tools
YT15	5	A02-B02-I04-C02- η 04	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20 $\pm$ 2°C recommended.

Humidity: 30%-70%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Appendix C (Informative Appendix) Defect Assessment Improvement Tool

Image analysis software : such as ImageJ, for pore and inclusion statistics with an accuracy of <0.1 μm .

EDS analyzer : used for inclusion composition analysis, detection limit <0.01%.

Magnetic property tester : evaluate the influence of η phase, magnetic saturation intensity deviation <5%.

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appendix:

ISO 4884:2019

Determination method of magnetic properties of cemented carbide

1 Scope

This standard specifies the determination method of magnetic saturation strength and coercive force (H_c) of cemented carbide, using the hysteresis loop method, and is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC, VC). This standard is applicable to the evaluation of cobalt phase quality and microstructure, and is widely used in quality control of cemented carbide manufacturing process.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

IEC 60404-4:1995 Magnetic materials Part 4: Methods of measurement of magnetic properties

3 Terms and definitions

This standard adopts ISO 3850:2018 and IEC 60404-4:1995 and the following terms and definitions:
Magnetic saturation intensity: The saturation magnetization intensity reached by the cobalt phase in cemented carbide under an external strong magnetic field, measured in T (Tesla), reflecting the cobalt phase content and purity.

Coercive force (H_c): The magnetic field strength required to demagnetize the magnetization intensity of cemented carbide from the saturation state to zero, expressed in A/m (ampere/meter), reflecting the microstructural characteristics.

Hysteresis loop: A closed curve showing the change of magnetization intensity with external magnetic field, used to measure magnetic properties.

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

The determination of magnetic properties is based on the hysteresis loop method, which is to place the sample in a closed magnetic circuit, apply a changing external magnetic field, record the relationship between magnetization intensity and magnetic field intensity, and draw a hysteresis loop. The magnetic saturation intensity is measured from the saturation region of the hysteresis loop, and the coercive force is determined from the zero-point magnetic field intensity during the demagnetization process.

Magnetic saturation intensity: It measures the maximum magnetization intensity of a sample in a

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strong magnetic field (>500 kA/m), usually standardized as the magnetization value per unit mass or unit volume.

Coercivity (H_c): A measure of the magnetic field strength required to reverse the magnetization from saturation to zero.

5. Measurement equipment

5.1 Magnetic Performance Tester

Magnetic field strength range: 0-1000 kA/m, accuracy $\pm 1\%$.

Magnetization intensity measurement range: 0-2 T, accuracy $\pm 0.5\%$.

Frequency: 50-60 Hz, suitable for DC or low frequency measurements.

Equipped with a closed magnetic circuit device (such as an electromagnet or a toroidal coil).

5.2 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width <0.5 mm, equipped with cooling system.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

5.3 Environmental Control

Temperature: 15°C to 30°C , $23\pm 2^{\circ}\text{C}$ recommended.

Humidity: 30%-70%, $50\pm 10\%$ recommended.

No external magnetic field interference (<5 A/m), no vibration, and no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size: $10\times 10\times 5$ mm or 10 mm in diameter and 5 mm in height.

The surface of the specimen should be flat, free of cracks, pores or oxide layer, and the surface roughness $R_a < 0.1\ \mu\text{m}$.

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the standard deviation of the results is $>5\%$, the number of samples needs to be increased to 5.

6.3 Specimen cutting and polishing

The specimens were cut using a low-speed precision cutting machine with a cutting speed of <0.1 mm/s and ethanol or water as the coolant.

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness $R_a < 0.1\ \mu\text{m}$.

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6.4 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Measurement steps

7.1 Equipment Calibration

Calibrate the magnetic field strength of the magnetic performance tester with a deviation of $\leq \pm 1\%$.

Calibrate the magnetization intensity measurement accuracy, the deviation is $\leq \pm 0.5\%$.

Use a standard sample (such as pure nickel) to verify the equipment, with a deviation of $\leq \pm 2\%$.

7.2 Test conditions

Ambient temperature: 15°C to 30°C, 23±2°C recommended.

Relative humidity: 30%-70%, 50±10% recommended.

No external magnetic field interference (< 5 A/m), no vibration, and no corrosive gas environment.

7.3 Test operation

Place the specimen in a closed magnetic circuit apparatus, ensuring that the specimen is aligned with the coil or magnetic poles.

A gradually increasing external magnetic field was applied until saturation (> 500 kA/m) was reached.

Record the changes in magnetization intensity and magnetic field intensity and draw the hysteresis loop.

The magnetic saturation intensity (normalized per unit mass or volume) is read from the hysteresis loop.

The coercivity (H_c), i.e. the magnetic field strength at which the magnetization is zero, is read from the demagnetization process.

Repeat the measurement 3-5 times and record each set of data.

7.4 Result calculation

Magnetic saturation intensity: measured in T or $A \cdot m^2 / kg$, usually converted to $4\pi Ms$ (Gauss unit, $1 T \approx 10^4$ Gauss).

Coercive force (H_c): measured in A/m.

Calculate the average:

$$\bar{Ms} = \frac{\sum Ms_i}{n}, \quad \bar{Hc} = \frac{\sum Hc_i}{n}$$

Where Ms_i and Hc_i are single measurement values, and n is the number of measurements.

Calculate the standard deviation:

$$s_{Ms} = \sqrt{\frac{\sum (Ms_i - \bar{Ms})^2}{n-1}}, \quad s_{Hc} = \sqrt{\frac{\sum (Hc_i - \bar{Hc})^2}{n-1}}$$

Qualification judgment: average value deviation $\leq \pm 5\%$, standard deviation $< 5\%$ (magnetic

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saturation intensity), <50 A/m (coercive force).

8 Evaluation of measurement results

8.1 Magnetic Property Range

The magnetic properties of cemented carbide range depends on the grade:

YG6 (6% Co): magnetic saturation intensity 0.15-0.18 T, coercive force 10-20 kA/m.

YG8 (8% Co): magnetic saturation intensity 0.20-0.24 T, coercive force 8-15 kA/m.

YT15 (5% Co + TiC): magnetic saturation intensity 0.12-0.15 T, coercive force 15-25 kA/m.

8.2 Deviation Assessment

of 3-5 samples is $\leq \pm 5\%$, the standard deviation is $\leq 5\%$ (magnetic saturation intensity), and ≤ 50 A/m (coercive force), otherwise retesting is required.

If the result is lower than the technical requirement, the reasons need to be analyzed (such as uneven distribution of cobalt phase and influence of impurities).

8.3 Analysis of influencing factors

Sample preparation: Surface roughness $> 0.1 \mu\text{m}$ or porosity $> 0.5\%$ may reduce the magnetic saturation intensity by 3%-5%.

Magnetic field interference: External magnetic field > 5 A/m may cause measurement errors of 2%-3%.

Material composition: Cobalt content fluctuation $> \pm 0.5\%$ or the presence of η phase may reduce the magnetic saturation intensity by 5%-10% and increase the coercive force by 10%-20%.

Equipment calibration: A deviation in magnetic field strength $> 1\%$ may result in a 2%-5% deviation in the results.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size ($10 \times 10 \times 5$ mm or diameter 10 mm, height 5 mm).

Test conditions: tester model, magnetic field strength (> 500 kA/m), ambient temperature (15°C to 30°C), humidity (30%-70%).

Test results: magnetic saturation intensity and coercivity of each sample, mean value, standard deviation and deviation.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Magnetic Properties of Typical Cemented Carbides

Brand	Co content (wt %)	Magnetic saturation intensity (T)	Coercive force (kA/m)	Typical Applications
YG6	6	0.15-0.18	10-20	Mining drill bits

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Brand	Co content (wt %)	Magnetic saturation intensity (T)	Coercive force (kA/m)	Typical Applications
YG8	8	0.20-0.24	8-15	Cutting Tools
YT15	5	0.12-0.15	15-25	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 15°C to 30°C, 23±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No external magnetic field interference (<5 A/m), no vibration, and no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

ISO 4884:2019 "Methods for determination of magnetic properties of cemented carbide" provides an international standardized procedure for the determination of magnetic saturation strength and coercivity of cemented carbide, and ensures the accuracy and comparability of the results through the hysteresis loop method . The implementation of this standard helps to evaluate the quality and microstructure of the cobalt phase and provide technical support for quality control of the cemented carbide manufacturing process.

appendix:

ISO 3369:2006

Method for determination of density of cemented carbide

1 Scope

This standard specifies the determination method of cemented carbide density, using the Archimedean principle, and is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC, VC). This standard is applicable to quality control and material composition verification, and is widely used in cutting tools, wear-resistant parts and other application fields.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

3 Terms and definitions

This standard adopts ISO 3850:2018 and the following terms and definitions:

Density: A measure of mass per unit volume, expressed in g/cm^3 , reflecting the compactness of cemented carbide.

Archimedes' principle: a method of measuring density based on the relationship between the volume of liquid displaced by an object in a liquid and its mass.

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

The density is determined based on the Archimedean principle. The density of the sample is calculated by measuring the mass of the sample in the air and the mass held up by buoyancy in the liquid. The formula is:

$$\rho = \frac{m_a \cdot \rho_l}{m_a - m_l}$$

其中:

- ρ 为试样密度 (g/cm^3),
- m_a 为试样在空气中的质量 (g),
- m_l 为试样在液体中的质量 (g),
- ρ_l 为液体的密度 (g/cm^3 , 通常为去离子水的 0.997 g/cm^3 , 20°C).

in:

ρ is the sample density (g/cm^3),

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m_a is the mass of the sample in air (g),

m_l is the mass of the sample in the liquid (g),

ρ_l is the density of the liquid (g/cm^3), typically 0.997 g/cm^3 for deionized water at 20°C .

5. Measurement equipment

5.1 Balance

Measuring range: 0-200 g, accuracy $\pm 0.0001 \text{ g}$.

Equipped with a suspension device for measuring in liquids.

5.2 Liquid Container

Material: corrosion-resistant glass or stainless steel.

Liquid: deionized water, temperature controlled at $20 \pm 1^\circ\text{C}$.

5.3 Thermometer

Measuring range: 0°C to 50°C , accuracy $\pm 0.1^\circ\text{C}$.

5.4 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width $< 0.5 \text{ mm}$, equipped with cooling system.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

5.5 Environmental Control

Temperature: 15°C to 25°C , $20 \pm 1^\circ\text{C}$ recommended.

Humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: any shape, recommended size $10 \times 10 \times 5 \text{ mm}$ or total mass $\geq 5 \text{ g}$.

The surface of the specimen should be flat, free of cracks, pores or oxide layer, and the surface roughness $R_a < 0.1 \mu\text{m}$.

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the standard deviation of the results is $> 0.05 \text{ g/cm}^3$, the number of samples needs to be increased to 5.

6.3 Specimen cutting and polishing

The specimens were cut using a low-speed precision cutting machine with a cutting speed of $< 0.1 \text{ mm/s}$ and ethanol or water as the coolant.

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Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness Ra <0.1 μm .

6.4 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Measurement steps

7.1 Equipment Calibration

The accuracy of the calibrated balance is <±0.0001 g.

Thermometer was calibrated with a deviation of < ±0.1°C.

7.2 Test conditions

Ambient temperature: 15°C to 25°C, 20±1°C recommended.

Liquid temperature: 20±1°C.

Relative humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

Measure the mass of the sample in air, m_a , and record to 0.0001 g.

Suspend the sample under a balance, immerse it in deionized water, measure its mass in the liquid (m_l), and record to 0.0001 g.

Make sure the specimen is completely immersed and free of air bubbles.

Repeat the measurement 3-5 times and record each set of data.

7.4 Result calculation

Calculate the density of each specimen:

$$\rho = \frac{m_a + \rho_l}{m_a - m_l}$$

where $\rho_l = 0.997 \text{ g/cm}^3$ (20°C).

Calculate the average:

$$\bar{\rho} = \frac{\sum \rho_i}{n}$$

Where ρ_i is the density of a single sample and n is the number of samples.

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (\rho_i - \bar{\rho})^2}{n - 1}}$$

Qualification judgment: average density deviation <±0.5%, standard deviation <0.05 g/cm³ .

8 Evaluation of measurement results

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8.1 Density range

The density range of cemented carbide depends on the grade:

YG6 (6% Co): 14.8-15.0 g/ cm³ .

YG8 (8% Co): 14.6-14.8 g/ cm³ .

YT15 (5% Co + TiC): 11.5-12.0 g/ cm³ .

8.2 Deviation Assessment

The average density deviation of 3-5 samples is $\leq \pm 0.5\%$, and the standard deviation is $< 0.05 \text{ g/cm}^3$, otherwise retesting is required.

If the density is lower than the technical requirements, the reasons need to be analyzed (such as high porosity and composition deviation).

8.3 Analysis of influencing factors

Sample preparation: Surface roughness $> 0.1 \mu\text{m}$ or cracks $> 0.05 \text{ mm}$ may cause density measurement errors of 0.1%-0.2%.

Liquid temperature: A temperature deviation of $> 1^\circ\text{C}$ from 20°C may result in a density deviation of 0.05%-0.1%.

Bubble adhesion: Bubbles on the sample surface may reduce the measured value by 0.1%-0.3%.

Material composition: Co content fluctuations $> \pm 0.5\%$ or insufficient WC content may affect density uniformity.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size ($10 \times 10 \times 5 \text{ mm}$ or total mass $\geq 5 \text{ g}$).

Test conditions: balance model, liquid temperature ($20 \pm 1^\circ\text{C}$), ambient temperature (15°C to 25°C), humidity (30%-70%).

Test results: density, mean value, standard deviation and deviation of each specimen.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Typical Carbide Density Reference Values

Brand	Co content (wt %)	Density(g/ cm ³)	Typical Applications
YG6	6	14.8-15.0	Mining drill bits
YG8	8	14.6-14.8	Cutting Tools
YT15	5	11.5-12.0	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 15°C to 25°C , $20 \pm 1^\circ\text{C}$ recommended.

Humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

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Test bench levelness: deviation <0.02 mm/m.

Summarize

ISO 3369:2006 "Determination of density of cemented carbide" provides an international standardized procedure for the determination of cemented carbide density, ensuring the accuracy and comparability of the results through the Archimedean principle. The implementation of this standard helps quality control and material composition verification, and provides technical support for application areas such as cutting tools and wear-resistant parts.

appendix:

ISO 28079:2009

Determination method of fracture toughness of cemented carbide

1 Scope

This standard specifies the determination method of the fracture toughness (K_{IC} K_{IC}) of cemented carbide, using the single edge notched beam (SENB) test method, and is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC , TiC , NbC , VC). This standard is applicable to the evaluation of the ability of cemented carbide to resist crack propagation, and is widely used for performance analysis in high stress application fields such as cutting tools and wear-resistant parts.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

ISO 12135:2002 Metallic materials — Test methods for fracture toughness

3 Terms and definitions

This standard adopts ISO 3850:2018 and ISO 12135:2002 and the following terms and definitions:
Fracture toughness (K_{IC} K_{IC}) : The ability of a material to resist crack growth, expressed in $\text{MPa} \cdot \text{m}^{1/2}$, measured under plane strain conditions.

Single Edge Notched Beam (SENB): A beam specimen with a notch on one side, used for fracture toughness testing.

Pre-crack: The initial crack generated by fatigue loading at the notched end of the specimen.

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

Fracture toughness (K_{IC} K_{IC}) is determined based on the single edge notched beam (SENB) test, which measures the critical stress intensity factor at fracture of a specimen by applying a concentrated load to the specimen. K_{IC} K_{IC} is calculated using the following formula:

$$K_{IC} = \frac{F}{B\sqrt{W}} \cdot Y \cdot f\left(\frac{a}{W}\right)$$

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其中:

- K_{IC} 为断裂韧性 ($\text{MPa}\cdot\text{m}^{1/2}$) ,
 - F 为断裂载荷 (N) ,
 - B 为试样厚度 (m) ,
 - W 为试样宽度 (m) ,
 - a 为切口深度 (m) ,
 - Y 为几何因子 (取决于 a/W 比) ,
 - $f\left(\frac{a}{W}\right)$ 为校正函数 (基于标准表或公式) ,
- a/W 比通常在 0.45 至 0.55 之间。

5. Measurement equipment

5.1 Testing machine

Loading capacity: 0-50 kN , accuracy $\pm 1\%$.

Loading speed: 0.1-1 mm/min, adjustable.

Equipped with force sensor and displacement sensor with resolution <0.01 N and <0.01 mm.

5.2 Fatigue loading equipment

Loading frequency: 10-30 Hz, accuracy ± 1 Hz.

Maximum load: not more than 80% of bending strength, accuracy $\pm 1\%$.

5.3 Fixture

Three-point bending fixture: support point radius 1-2 mm, loading point radius 1 mm, support span 16-20 mm.

Clamp material: Hardened steel, hardness $>\text{HRC } 60$.

5.4 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width <0.1 mm, equipped with cooling system.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

5.5 Environmental Control

Temperature: 10°C to 35°C , $23\pm 2^{\circ}\text{C}$ recommended.

Humidity: 30%-70%, $50\pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: cuboid, recommended size: $20\times 4\times 2$ mm (length $\times$ width $\times$ height), tolerance ± 0.02 mm.

Incision: Depth a is the width of the specimen W 45%-55% of W , incision width <0.1 mm, tip radius <0.05 mm.

The surface of the specimen should be flat, without cracks or oxide layer, and the surface roughness

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$Ra < 0.02 \mu m$.

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure statistical representativeness. If the standard deviation of the results is $> 0.2 MPa \cdot m^{1/2}$, the number of samples needs to be increased to 10.

6.3 Specimen cutting and polishing

The specimens were cut using a low-speed precision cutting machine with a cutting speed of $< 0.05 mm/s$ and ethanol or water as the coolant.

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness $Ra < 0.1 \mu m$.

Polishing: Use $0.25 \mu m$ aluminum oxide polishing liquid, surface roughness $Ra < 0.02 \mu m$.

6.4 Pre-crack preparation

A fatigue loading device was used to generate a pre-crack at the notch end, with a load range of 50%-80% of the bending strength and a frequency of 10-30 Hz.

The pre-crack length increased by 0.5-1 mm and the tip radius was $< 0.01 mm$.

6.5 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Measurement steps

7.1 Equipment Calibration

Calibrate the testing machine loading accuracy, deviation $< \pm 1\%$.

Calibrate the fixture centering, deviation $< 0.02 mm$.

Calibrate fatigue loading equipment load and frequency with a deviation of $< \pm 1\%$.

7.2 Test conditions

Ambient temperature: $10^{\circ}C$ to $35^{\circ}C$, $23 \pm 2^{\circ}C$ recommended.

Relative humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

The specimen was placed in a three-point bending fixture with the support point aligned with the loading point and a span of 16 mm.

Adjust the loading speed to $0.5 \pm 0.2 mm/min$.

Apply load until the specimen breaks, and record the maximum load F and fracture displacement.

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The notch depth a and the sample width W were measured and the a/W ratio was calculated.
Repeat the experiment 5-10 times and record each set of data.

7.4 Result calculation

Calculate the fracture toughness KIC of each specimen according to the formula in Section 4 .

几何因子 Y 和校正函数 $f\left(\frac{a}{W}\right)$ 参考标准表 (附录 A) 。

Calculate the average:

$$\bar{K}_{IC} = \frac{\sum K_{ICi}}{n}$$

Where K_{ICi} is the fracture toughness of a single specimen and n is the number of specimens.

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (K_{ICi} - \bar{K}_{IC})^2}{n - 1}}$$

Qualification judgment: average fracture toughness deviation $< \pm 5\%$, standard deviation $< 0.2 \text{ MPa} \cdot \text{m}^{1/2}$.

8 Evaluation of measurement results

8.1 Fracture toughness range

The fracture toughness range of cemented carbide depends on the grade:

YG6 (6% Co): $12\text{-}15 \text{ MPa} \cdot \text{m}^{1/2}$.

YG8 (8% Co): $10\text{-}13 \text{ MPa} \cdot \text{m}^{1/2}$.

YT15 (5% Co + TiC): $8\text{-}11 \text{ MPa} \cdot \text{m}^{1/2}$.

8.2 Deviation Assessment

5-10 specimens is $< \pm 5\%$, and the standard deviation is $< 0.2 \text{ MPa} \cdot \text{m}^{1/2}$, otherwise retesting is required.

If the fracture toughness is lower than the technical requirements, the reasons need to be analyzed (such as uneven pre-cracks and specimen defects).

8.3 Analysis of influencing factors

Specimen preparation: Notch width $> 0.1 \text{ mm}$ or uneven pre-cracks may reduce the fracture toughness by 5%-10%.

Loading conditions: Loading speed $> 1 \text{ mm/min}$ or fixture centering deviation $> 0.05 \text{ mm}$ may cause result deviation of 3%-5%.

Material composition: Co content fluctuation $> \pm 0.5\%$ or WC grain size $> 2 \mu\text{m}$ may affect toughness uniformity.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size ($20 \times 4 \times 2 \text{ mm}$), notch depth a and a/W ratio.

Test conditions: testing machine model, fixture type (three-point), loading speed ($0.5 \pm 0.2 \text{ mm/min}$), ambient temperature (10°C to 35°C), humidity (30%-70%).

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Test results: fracture toughness, mean value, standard deviation and variation of each specimen.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Normative Appendix) Geometric factors and correction function tables

a/W ratio	Geometry factor Y	Correction function f(aW)
0.45	1.92	3.08
0.50	2.00	3.47
0.55	2.10	3.92

Note: Specific values are interpolated from standard tables based on specimen geometry and loading conditions.

Appendix B (Informative Appendix) Reference values of fracture toughness of typical cemented carbides

Brand	Co content (wt %)	Fracture toughness (MPa·m ^{1/2})	Typical Applications
YG6	6	12-15	Mining drill bits
YG8	8	10-13	Cutting Tools
YT15	5	8-11	Finishing tools

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 23±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

ISO 28079:2009 "Method for determination of fracture toughness of cemented carbide" provides an international standardized procedure for the determination of fracture toughness (KIC) of cemented carbide, and ensures the accuracy and comparability of the results through the single-edge notched beam (SENB) test. The implementation of this standard helps to evaluate the performance of cemented carbide and provides technical support for high-stress application fields such as cutting tools and wear-resistant parts.

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appendix:

ISO 3878:1983

Cemented Carbide Rockwell Hardness Test Method (HRA Scale)

1 Scope

This standard specifies the determination method of the Rockwell hardness (HRA scale) of cemented carbide, using a Rockwell hardness tester to apply an initial load of 10 kgf (98.07 N) and a total load of 60 kgf (588.4 N). It is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC, VC). This standard is suitable for rapid evaluation of the indentation resistance of cemented carbide and is widely used in the quality control of cutting tools and wear-resistant parts.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

ISO 6508-1:2005 Rockwell hardness test for metallic materials Part 1: Test method (scales A, B, C, D, E, F, G, H, K, N, T)

3 Terms and definitions

This standard adopts ISO 3850:2018 and ISO 6508-1:2005 and the following terms and definitions:
Rockwell hardness (HRA): The hardness value based on the depth difference after the Rockwell indenter is pressed into the sample surface. The unit is HRA and it is suitable for high hardness materials.

Diamond cone indenter: A 120° apex angle diamond indenter used in Rockwell hardness testers.

Initial load: The initial force applied to the specimen, which has a value of 10 kgf (98.07 N).

Total load: Preliminary load plus main load, value is 60 kgf (588.4 N).

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

The Rockwell hardness (HRA scale) is determined by using a Rockwell hardness tester, which measures the depth difference after the indenter is pressed into the sample surface by applying an initial load of 10 kgf and a total load of 60 kgf. The hardness value is calculated using the following formula:

$$HRA = 100 - \frac{h}{0.002}$$

HRA is the Rockwell hardness value, h is the difference between the indentation depth after the total load is removed and the initial load depth (mm), and 0.002 mm is the unit depth of

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the Rockwell hardness scale. The HRA scale is applicable to the hardness range of 20-88 HRA and is usually used for high hardness materials such as cemented carbide.

5. Measurement equipment

5.1 Rockwell hardness tester

Load range: 10 kgf (preliminary load) + 50 kgf (main load) = 60 kgf (total load), accuracy $\pm 0.5\%$.

Indenter: 120° apex angle diamond cone, tip radius 0.2 mm, accuracy ± 0.01 mm.

Depth measurement: resolution 0.001 mm, accuracy ± 0.5 μm .

Loading time: preliminary load 2-8 s, total load 10-15 s, accuracy ± 1 s.

5.2 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width < 0.5 mm, equipped with cooling system.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

5.3 Environmental Control

Temperature: 10°C to 35°C, 23 $\pm$ 2°C recommended.

Humidity: 30%-70%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size is 10 $\times$ 10 $\times$ 5 mm or 10 mm in diameter and 5 mm in height.

The surface of the specimen should be flat, free of cracks, scratches or oxide layers, and the surface roughness Ra < 0.02 μm .

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure statistical representativeness. If the standard deviation of the results is > 2 HRA, the number of samples needs to be increased to 10.

6.3 Specimen cutting and polishing

The specimens were cut using a low-speed precision cutting machine with a cutting speed of < 0.1 mm/s and ethanol or water as the coolant.

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove the cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness Ra < 0.1 μm .

Polishing: Use 0.25 μm aluminum oxide polishing liquid, surface roughness Ra < 0.02 μm .

6.4 Sample cleaning

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Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Measurement steps

7.1 Equipment Calibration

Calibrate Rockwell hardness tester load, deviation $< \pm 0.5\%$.

Calibrate the indenter and depth measurement system to an accuracy of $< \pm 0.5 \mu\text{m}$.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $23 \pm 2^{\circ}\text{C}$ recommended.

Relative humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

Place the sample on the Rockwell hardness tester workbench and adjust the surface level.

Apply an initial load of 10 kgf, hold for 2-8 s, and record the initial depth.

A total load of 60 kgf was applied and maintained for 10-15 s, and the depth difference was recorded after the main load was removed.

Measure at least 3 different positions on the surface of the specimen, with an interval of $\geq 2.5 \text{ mm}$.

Repeat the experiment 5-10 times and record each set of data.

7.4 Result calculation

Directly read the HRA value displayed by the Rockwell hardness tester.

Calculate the average:

$$\bar{HRA} = \frac{\sum HRA_i}{n}$$

Where HRA_i is a single measurement value and n is the number of measurements.

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (HRA_i - \bar{HRA})^2}{n - 1}}$$

Qualification judgment: average hardness deviation $< \pm 2\%$, standard deviation $< 2 \text{ HRA}$.

8 Evaluation of measurement results

8.1 Hardness range

The Rockwell hardness (HRA) range of cemented carbide depends on the grade:

YG6 (6% Co): 85-90 HRA.

YG8 (8% Co): 83-88 HRA.

YT15 (5% Co + TiC): 87-92 HRA.

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8.2 Deviation Assessment

of 5-10 measurement points is $\leq \pm 2\%$, and the standard deviation is ≤ 2 HRA, otherwise retesting is required.

If the hardness is lower than the technical requirements, the reasons need to be analyzed (such as surface defects and uneven load).

8.3 Analysis of influencing factors

Sample preparation: Surface roughness $> 0.02 \mu\text{m}$ or cracks $> 0.05 \text{ mm}$ may reduce hardness by 2%-5%.

Loading time: Total loading time $< 10 \text{ s}$ or $> 15 \text{ s}$ may result in a measurement error of 1%-2%.

Environmental conditions: Humidity $> 70\%$ or temperature fluctuations $> 5^\circ\text{C}$ may affect depth measurement accuracy.

Material composition: Co content fluctuation $> \pm 0.5\%$ or WC grain size $> 2 \mu\text{m}$ may affect hardness uniformity.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size ($10 \times 10 \times 5 \text{ mm}$ or diameter 10 mm , height 5 mm).

Test conditions: Rockwell hardness tester model, load ($10 \text{ kgf} + 50 \text{ kgf} = 60 \text{ kgf}$), loading time (2-8 s preliminary, 10-15 s total), ambient temperature (10°C to 35°C), humidity (30%-70%).

Test results: hardness value at each point, average value, standard deviation and deviation.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Rockwell Hardness (HRA) of Typical Cemented Carbides

Brand	Co content (wt %)	Hardness (HRA)	Typical Applications
YG6	6	85-90	Mining drill bits
YG8	8	83-88	Cutting Tools
YT15	5	87-92	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C , $23 \pm 2^\circ\text{C}$ recommended.

Humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $< 0.02 \text{ mm/m}$.

Summarize

ISO 3878:1983 "Test Method for Rockwell Hardness of Cemented Carbide (HRA Scale)" provides an international standardized procedure for the determination of Rockwell hardness of cemented carbide, ensuring the rapidity and comparability of results through Rockwell hardness tester. The

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implementation of this standard helps to evaluate the performance of cemented carbide and provide technical support for application fields such as cutting tools and wear-resistant parts.

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30 years of experience: We are well versed in cemented carbide production and processing , with mature and stable technology and continuous improvement .

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appendix:

**ISO 3326:2013 Cemented Carbide
Vickers hardness test method**

1 Scope

This standard specifies the determination method of the Vickers hardness of cemented carbide, using a Vickers hardness tester to apply a load of 10-50 kgf (98.07-490.3 N). It is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC , TiC , NbC , VC). This standard is applicable to the evaluation of the indentation resistance of cemented carbide and is widely used in the quality control of cutting tools, wear-resistant parts and other application fields.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

ISO 6507-1:2005 Vickers hardness test for metallic materials Part 1: Test method

3 Terms and definitions

This standard adopts ISO 3850:2018 and ISO 6507-1:2005 and the following terms and definitions:
Vickers hardness (HV): A measure of the resistance to indentation per unit area of a specimen surface after the Vickers indenter is pressed into the specimen surface, expressed in HV (hardness value).

Vickers indenter: A quadrangular pyramid indenter made of diamond with a vertex angle of 136°.

Load: The force applied to the specimen, ranging from 10-50 kgf (98.07-490.3 N).

Cemented carbide: A composite material made by powder metallurgy process with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase.

4. Determination principle

The determination of Vickers hardness is based on the Vickers hardness tester, which presses a diamond quadrangular pyramid indenter into the sample surface with a specific load, measures the diagonal length of the indentation, and calculates the indentation resistance per unit area. The hardness value is calculated according to the following formula:

$$HV = \frac{1.8544F}{d^2}$$

HV HV HV is Vickers hardness (kgf / mm²), F F F is the applied load (kgf), d d d is the average length of the two diagonals of the indentation (mm). The result is usually converted to HV10 or HV30, depending on the load.

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5. Measurement equipment

5.1 Vickers hardness tester

Load range: 10-50 kgf (98.07-490.3 N), accuracy $\pm 1\%$.

Indenter: Diamond quadrangular pyramid, vertex angle $136^{\circ} \pm 0.5^{\circ}$.

Microscope: magnification 200 $\times$ -500 $\times$, resolution < 0.001 mm.

Loading time: 10-15 s, accuracy ± 1 s.

5.2 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width < 0.5 mm, equipped with cooling system.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

5.3 Environmental Control

Temperature: 10°C to 35°C, $23 \pm 2^{\circ}\text{C}$ recommended.

Humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size is 10 $\times$ 10 $\times$ 5 mm or 10 mm in diameter and 5 mm in height.

The surface of the specimen should be flat, free of cracks, scratches or oxide layers, and the surface roughness $R_a < 0.02$ μm .

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure statistical representativeness. If the standard deviation of the results is > 20 HV, the number of samples needs to be increased to 10.

6.3 Specimen cutting and polishing

The specimens were cut using a low-speed precision cutting machine with a cutting speed of < 0.1 mm/s and ethanol or water as the coolant.

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove the cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness $R_a < 0.1$ μm .

Polishing: Use 0.25 μm aluminum oxide polishing liquid, surface roughness $R_a < 0.02$ μm .

6.4 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

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After drying, store in a desiccator to avoid oxidation or contamination.

7 Measurement steps

7.1 Equipment Calibration

Calibrate Vickers hardness tester load, deviation $< \pm 1\%$.

The microscope magnification and diagonal measurement accuracy were calibrated to a deviation of $< \pm 0.5\%$.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $23 \pm 2^{\circ}\text{C}$ recommended.

Relative humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

Place the sample on the Vickers hardness tester workbench and adjust the surface level.

Select load: 10 kgf (HV10) or 30 kgf (HV30), depending on the thickness and grade of the specimen.

Apply the load for 10-15 s and measure the length of the two diagonals of the indentation after removing the load . d .

Measure at least 3 different positions on the surface of the specimen, with an interval of $\geq 2.5 \text{ mm}$.

Repeat the experiment 5-10 times and record each set of data.

7.4 Result calculation

Calculate the Vickers hardness of each specimen:

$$HV = \frac{1.8544F}{d^2}$$

Where F is the load (kgf) and d is the average diagonal length of the indentation (mm).

Calculate the average:

$$\bar{HV} = \frac{\sum HV_i}{n}$$

Where HV_i is a single measurement value and n is the number of measurements.

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (HV_i - \bar{HV})^2}{n - 1}}$$

Qualification: Average hardness deviation $< \pm 5\%$, standard deviation $< 20 \text{ HV}$.

8 Evaluation of measurement results

8.1 Hardness range

The Vickers hardness range of cemented carbide depends on the grade:

YG6 (6% Co): 1400-1600 HV30.

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YG8 (8% Co): 1300-1500 HV30.
YT15 (5% Co + TiC): 1500-1700 HV10.

8.2 Deviation Assessment

of 5-10 measurement points is $<\pm 5\%$, and the standard deviation is <20 HV, otherwise retesting is required.

If the hardness is lower than the technical requirements, the reasons need to be analyzed (such as surface defects, insufficient load).

8.3 Analysis of influencing factors

Sample preparation: Surface roughness $> 0.02 \mu\text{m}$ or cracks $> 0.05 \text{ mm}$ may reduce hardness by 5%-10%.

Load selection: A load that is too low ($<10 \text{ kgf}$) or too high ($>50 \text{ kgf}$) may result in a measurement error of 3%-5%.

Environmental conditions: Humidity $>70\%$ or temperature fluctuations $>5^\circ\text{C}$ may affect indentation clarity.

Material composition: Co content fluctuation $> \pm 0.5\%$ or WC grain size $> 2 \mu\text{m}$ may affect hardness uniformity.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size ($10 \times 10 \times 5 \text{ mm}$ or diameter 10 mm , height 5 mm).

Test conditions: Vickers hardness tester model, load (10 kgf or 30 kgf), loading time ($10-15 \text{ s}$), ambient temperature (10°C to 35°C), humidity ($30\%-70\%$).

Test results: hardness value at each point, average value, standard deviation and deviation.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference values of Vickers hardness of typical cemented carbides

Brand	Co content (wt %)	Load (kgf)	Hardness (HV)	Typical Applications
YG6	6	30	1400-1600	Mining drill bits
YG8	8	30	1300-1500	Cutting Tools
YT15	5	10	1500-1700	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C , $23 \pm 2^\circ\text{C}$ recommended.

Humidity: $30\%-70\%$, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $<0.02 \text{ mm/m}$.

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Summarize

ISO 3326:2013 "Test Method for Vickers Hardness of Cemented Carbide" provides an international standardized procedure for the determination of Vickers hardness of cemented carbide, ensuring the accuracy and comparability of the results through the Vickers hardness tester. The implementation of this standard helps to evaluate the performance of cemented carbide and provides technical support for application areas such as cutting tools and wear-resistant parts.

appendix:

ISO 4489-2:2020
Cemented Carbide
Determination method of flexural strength
Part 2: High temperature conditions

1 Scope

This standard specifies the determination method of the flexural strength of cemented carbide under high temperature conditions (above 35°C), using a three-point or four-point bending test, and is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC, VC). As part of the ISO 4489 series, this standard supplements the room temperature test method of ISO 4489:2010 and is applicable to performance evaluation in high temperature environments, such as aerospace and high temperature cutting tool applications.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 4489:2010 Method for determination of flexural strength of cemented carbide

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

3 Terms and definitions

This standard adopts ISO 3850:2018 and the following terms and definitions:

Flexural strength: The maximum stress that a specimen withstands in a high-temperature bending test, measured in MPa, reflects the material's ability to resist fracture at high temperatures.

Three-point bending test: A single load point is applied between two supporting points to measure the maximum stress at which the specimen breaks.

Four-point bending test: Two loading points are applied between two supporting points to measure the maximum stress when the specimen breaks.

High temperature conditions: The test temperature is above 35°C, usually in the range of 200°C to 1200°C.

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4. Determination principle

The determination of flexural strength is based on a high temperature bending test, where loads are applied by three-point or four-point loading to measure the maximum stress at break of the specimen at high temperature. The stress calculation is based on the specimen geometry and loading conditions using the following formula:

Three-point bending:

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$$\sigma = \frac{3FL}{2bh^2}$$

Where σ is the flexural strength (MPa), F is the breaking load (N), L is the support span (mm), b is the specimen width (mm), and h is the specimen thickness (mm).

Four-point bending:

$$\sigma = \frac{3F(L_1 - L_2)}{bh^2}$$

Where L_1 is the external support span (mm) and L_2 is the internal loading span (mm).

Under high temperature conditions, material properties (such as yield point and fracture strength) change with temperature, and a high temperature furnace is required to control the environment and correct for thermal expansion effects.

5. Measurement equipment

5.1 Testing machine

Loading capacity: 0-50 kN , accuracy $\pm 1\%$.

Loading speed: 0.5-5 mm/min, adjustable.

Equipped with force sensor and displacement sensor with resolution <0.01 N and <0.01 mm.

5.2 High temperature furnace

Temperature range: 200°C to 1200°C, accuracy $\pm 5^\circ\text{C}$.

Heating rate: 5-10°C/min, stabilization time ≥ 30 min.

Protective atmosphere: inert gas (such as argon) or vacuum environment to prevent oxidation.

5.3 Fixture

Three-point bending fixture: support point radius 1-2 mm, loading point radius 1 mm.

Four-point bending fixture: outer support span 20-40 mm, inner loading span 10-20 mm, support point radius 1-2 mm.

Fixture material: high temperature resistant alloy (such as Inconel), working temperature $\geq 1200^\circ\text{C}$.

5.4 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width <0.5 mm, equipped with cooling system.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

5.5 Environmental Control

Temperature: 200°C to 1200°C (test temperature), outside environment 10°C to 35°C, recommended $23 \pm 2^\circ\text{C}$.

Humidity: 30%-70%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment (except protective atmosphere).

6. Sample preparation

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6.1 Sample requirements

Sample shape: cuboid, recommended size: 20×6.5×5.25 mm (length×width×height), tolerance ±0.1 mm.

The surface of the specimen should be flat and free of cracks, scratches or oxide layers.

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 10 to ensure statistical representativeness. If the standard deviation of the results is >50 MPa, the number of samples needs to be increased to 15.

6.3 Specimen cutting and polishing

The specimens were cut using a low-speed precision cutting machine with a cutting speed of <0.1 mm/s and ethanol or water as the coolant.

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness Ra <0.1 μm.

Polishing: Use 0.25 μm aluminum oxide polishing liquid, surface roughness Ra <0.02 μm.

6.4 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Measurement steps

7.1 Equipment Calibration

Calibrate the testing machine loading accuracy, deviation ≤±1%.

Calibrate the furnace temperature to within ±5°C.

Calibrate the fixture to a centering error of <0.05 mm.

7.2 Test conditions

Test temperature: 200°C to 1200°C, the specific temperature is set according to the material and application.

Heating time: After heating to the target temperature, stabilize for 30 minutes.

Protective atmosphere: Argon flow rate 0.5-1 L/min, or vacuum degree <10⁻² Pa.

7.3 Test operation

The specimen is placed in a three-point or four-point bending fixture in a high-temperature furnace with the support points aligned with the loading points.

The temperature was raised to the target temperature and stabilized for 30 min before the test began.

Adjust the loading speed to 1±0.5 mm/min.

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Apply load until the specimen breaks and record the maximum load F F F and fracture displacement.
Repeat the experiment 10-15 times and record each set of data.

7.4 Result calculation

Calculate the flexural strength σ of each specimen according to the formula in Section 4

Calculate the average:

$$\bar{\sigma} = \frac{\sum \sigma_i}{n}$$

Where σ_i is the flexural strength of a single specimen and n is the number of specimens.

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (\sigma_i - \bar{\sigma})^2}{n - 1}}$$

Qualification judgment: average flexural strength deviation $< \pm 5\%$, standard deviation < 50 MPa.

8 Evaluation of measurement results

8.1 Bending strength range

The high temperature bending strength range of cemented carbide depends on the grade and temperature:

YG6 (6% Co): 1500-2000 MPa (600°C).

YG8 (8% Co): 1300-1800 MPa (800°C).

YT15 (5% Co + TiC): 1000-1400 MPa (1000°C).

8.2 Deviation Assessment

of 10-15 specimens is $< \pm 5\%$, and the standard deviation is < 50 MPa, otherwise retesting is required.
If the flexural strength is lower than the technical requirements, the reasons (such as oxidation and sample defects) need to be analyzed.

8.3 Analysis of influencing factors

Temperature: Temperature $> 1000^\circ\text{C}$ may cause the Co phase to soften and the flexural strength to decrease by 20%-30%.

Oxidation: Insufficient protective atmosphere may lead to surface oxidation and a 10%-15% decrease in strength.

Specimen preparation: Surface roughness $> 0.02 \mu\text{m}$ or cracks $> 0.05 \text{ mm}$ may reduce strength by 5%-10%.

Loading conditions: Loading speed $> 5 \text{ mm/min}$ or fixture misalignment $> 0.1 \text{ mm}$ may result in a 5% deviation in the results.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size (20×6.5×5.25 mm).

Test conditions: testing machine model, high temperature furnace model, fixture type (three-point or four-point), loading speed (1±0.5 mm/min), test temperature (200°C to 1200°C), protective

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atmosphere, ambient temperature (10°C to 35°C), humidity (30%-70%).

Test results: flexural strength, mean value, standard deviation and deviation of each specimen.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of High-Temperature Bending Strength of Typical Cemented Carbides

Brand	Co content (wt %)	Temperature (°C)	Flexural strength(MPa)	Typical Applications
YG6	6	600	1500-2000	High temperature drill bit
YG8	8	800	1300-1800	High temperature cutting tools
YT15	5	1000	1000-1400	High temperature finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Test temperature: 200°C to 1200°C, accuracy $\pm 5^{\circ}\text{C}$.

Ambient temperature outside the furnace: 10°C to 35°C, $23\pm 2^{\circ}\text{C}$ is recommended.

Humidity: 30%-70%, $50\pm 10\%$ recommended.

No vibration, no corrosive gas environment (except protective atmosphere).

Test bench levelness: deviation $< 0.02\text{ mm/m}$.

Summarize

ISO 4489-2:2020 "Determination of flexural strength of cemented carbide - Part 2: High temperature conditions" provides an international standardized procedure for the determination of flexural strength of cemented carbide under high temperature conditions, through three-point or four-point bending tests to ensure the accuracy and comparability of the results. The implementation of this standard helps to evaluate performance in high temperature environments and provides technical support for aerospace, high temperature cutting tools and other application fields.

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appendix:

ISO 4489:2010
Cemented Carbide
Determination method of flexural strength

1 Scope

This standard specifies the determination method of the bending strength of cemented carbide, using a three-point or four-point bending test, and is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC, VC). This standard is applicable to the evaluation of the mechanical properties of cemented carbide and is widely used in cutting tools, wear-resistant parts and other application fields.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:2018 Cemented Carbide Terminology

3 Terms and definitions

This standard adopts ISO 3850:2018 and the following terms and definitions:

Flexural strength: The maximum stress that a specimen withstands in a bending test, measured in MPa, reflects the material's ability to resist fracture.

Three-point bending test: A single load point is applied between two supporting points to measure the maximum stress at which the specimen breaks.

Four-point bending test: Two loading points are applied between two supporting points to measure the maximum stress when the specimen breaks.

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4. Determination principle

The determination of flexural strength is based on a bending test, by applying a concentrated load (three-point method) or a uniformly distributed load (four-point method) to the specimen and measuring the maximum stress at the moment of specimen fracture. The stress calculation is based on the specimen geometry and loading conditions using the following formula:

Three-point bending:

$$\sigma = \frac{3FL}{2bh^2}$$

Where σ is the flexural strength (MPa), F is the breaking load (N), L is the support span (mm), b is the specimen width (mm), and h is the specimen thickness (mm).

Four-point bending:

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$$\sigma = \frac{3F(L_1 - L_2)}{bh^2}$$

Where L1 is the external support span (mm) and L2 is the internal loading span (mm).

5. Measurement equipment

5.1 Testing machine

Loading capacity: 0-50 kN , accuracy $\pm 1\%$.

Loading speed: 0.5-5 mm/min, adjustable.

Equipped with force sensor and displacement sensor with resolution <0.01 N and <0.01 mm.

5.2 Fixture

Three-point bending fixture: support point radius 1-2 mm, loading point radius 1 mm.

Four-point bending fixture: outer support span 20-40 mm, inner loading span 10-20 mm, support point radius 1-2 mm.

Clamp material: Hardened steel, hardness $>HRC$ 60.

5.3 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width <0.5 mm, equipped with cooling system.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

5.4 Environmental Control

Temperature: 10°C to 35°C , $23 \pm 2^{\circ}\text{C}$ recommended.

Humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: cuboid, recommended size: $20 \times 6.5 \times 5.25$ mm (length $\times$ width $\times$ height), tolerance ± 0.1 mm.

The surface of the specimen should be flat and free of cracks, scratches or oxide layers.

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 10 to ensure statistical representativeness.

If the standard deviation of the results is >50 MPa, the number of samples needs to be increased to 15 .

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6.3 Specimen cutting and polishing

The specimens were cut using a low-speed precision cutting machine with a cutting speed of <0.1 mm/s and ethanol or water as the coolant.

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness Ra <0.1 μm .

Polishing: Use 0.25 μm aluminum oxide polishing liquid, surface roughness Ra <0.02 μm .

6.4 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Measurement steps

7.1 Equipment Calibration

Calibrate the testing machine loading accuracy, deviation <±1%.

Calibrate the fixture to a centering error of <0.05 mm.

7.2 Test conditions

Ambient temperature: 10°C to 35°C, 23±2°C recommended.

Relative humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

Place the specimen in a three-point or four-point bending fixture with the support points aligned with the loading points.

Adjust the loading speed to 1±0.5 mm/min.

Apply load until the specimen breaks, and record the maximum load F and fracture displacement.

Repeat the experiment 10-15 times and record each set of data.

7.4 Result calculation

Calculate the flexural strength σ of each specimen according to the formula in Section 4.

Calculate the average:

$$\bar{\sigma} = \frac{\sum \sigma_i}{n}$$

Where σ_i is the flexural strength of a single specimen and n is the number of specimens.

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (\sigma_i - \bar{\sigma})^2}{n - 1}}$$

Qualification judgment: average flexural strength deviation <±5%, standard deviation <50 MPa.

8 Evaluation of measurement results

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8.1 Bending strength range

The bending strength range of cemented carbide depends on the grade:

YG6 (6% Co): 2000-2500 MPa.

YG8 (8% Co): 1800-2200 MPa.

YT15 (5% Co + TiC): 1300-1600 MPa.

8.2 Deviation Assessment

of 10-15 specimens is $\leq \pm 5\%$, and the standard deviation is < 50 MPa, otherwise retesting is required. If the flexural strength is lower than the technical requirements, the reasons need to be analyzed (such as specimen defects and uneven loading).

8.3 Analysis of influencing factors

Specimen preparation: Surface roughness $> 0.02 \mu\text{m}$ or cracks $> 0.05 \text{ mm}$ may reduce the flexural strength by 10%-15%.

Loading conditions: Loading speed $> 5 \text{ mm/min}$ or fixture misalignment $> 0.1 \text{ mm}$ may cause a 5%-10% deviation in the results.

Material composition: Co content fluctuation $> \pm 0.5\%$ or WC grain size $> 2 \mu\text{m}$ may affect strength uniformity.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size (20×6.5×5.25 mm).

Test conditions: testing machine model, fixture type (three-point or four-point), loading speed (1±0.5 mm/min), ambient temperature (10°C to 35°C), humidity (30%-70%).

Test results: flexural strength, mean value, standard deviation and deviation of each specimen.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Bending Strength of Typical Cemented Carbides

Brand	Co content (wt %)	Flexural strength(MPa)	Typical Applications
YG6	6	2000-2500	Mining drill bits
YG8	8	1800-2200	Cutting Tools
YT15	5	1300-1600	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 23±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $< 0.02 \text{ mm/m}$.

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Summarize

ISO 4489:2010 "Determination of flexural strength of cemented carbide" provides an international standardized procedure for the determination of flexural strength of cemented carbide, through three-point or four-point bending test, to ensure the accuracy and comparability of the results. The implementation of this standard is conducive to the performance evaluation of cemented carbide and provides technical support for application fields such as cutting tools and wear-resistant parts.

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appendix:

ISO 4499-3:2016 Cemented Carbide

— Microstructure inspection

Part 3: Assessment of porosity, inclusions, free carbon and eta phase

1 Scope

This standard specifies the evaluation method of defects such as pores, inclusions, free carbon and η phase in the microstructure of cemented carbide, and uses metallographic microscope observation and standard atlas for grading. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC, VC). This standard is part of the ISO 4499 series of standards and must be used in conjunction with ISO 4499-1:2006.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 4499-1:2006 Cemented carbide — Microstructure examination Part 1: General guidance

ISO 3847:2005 Methods for preparation of cemented carbide specimens

3 Terms and definitions

This standard adopts ISO 3850:2018 (latest version) and the following terms and definitions:

Porosity: Pores or spaces in a microstructure, divided into Type A (diameter $<10\ \mu\text{m}$) and Type B (diameter $10\text{--}25\ \mu\text{m}$).

Inclusions: Non-metallic impurities (such as oxides and sulfides) that exist in cemented carbide in the form of particles.

Free carbon: Carbon that does not form compounds with metals and exists in the form of graphite.

η phase: A brittle phase formed due to insufficient carbon content, such as $\text{W}_3\text{Co}_3\text{C}$ or $\text{Co}_6\text{W}_6\text{C}$.

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4 Assessment Principles

The evaluation of cemented carbide microstructure defects is based on metallographic microscope observation, combined with standard atlas (Appendix A) to grade the type, size, quantity and distribution of pores, inclusions, free carbon and η phase. The evaluation method is to prepare high-quality samples, observe them in bright field and polarized light, record the defect characteristics, and compare them with the standard atlas to determine the defect grade.

5. Assessment equipment

5.1 Metallographic microscope

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Magnification: 100×, 200×, 500×, 200× is recommended for routine observation.
Equipped with brightfield, darkfield and polarized light capabilities to differentiate defect types.
Resolution: <0.5 μm .

5.2 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width <0.5 mm, equipped with cooling system.
Mounting machine: hot press mounting, temperature <150°C, pressure 20-30 MPa.
Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.
Ultrasonic cleaner: frequency 40 kHz, used to clean samples.

5.3 Measurement tools

Eyepiece micrometer: graduation value 0.01 mm, accuracy ±0.001 mm.
Image analysis software: supports defect area and quantity statistics, with an accuracy of ±0.1 μm .

5.4 Environmental Control

Temperature: 10°C to 35°C, 20±2°C recommended.
Humidity: 30%-70%, 50±10% recommended.
No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size: 10×10× 5 mm.
The surface of the specimen should be flat and free of cracks, scratches or oxide layers.
The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.
If the result deviation is large (>1 level), the number of samples needs to be increased to 5 .

6.3 Specimen cutting and mounting

The specimens were cut using a low-speed precision cutting machine with a cutting speed of <0.1 mm/s and ethanol or water as the coolant.
Hot press mounting, temperature <150°C, pressure 20-30 MPa, time 5-10 min.

6.4 Grinding and polishing of specimens

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.
Fine grinding: Use 2500# sandpaper, surface roughness Ra <0.1 μm .
Polishing: Use 0.25 μm aluminum oxide polishing paste, polishing cloth speed 300 r/min, surface roughness Ra <0.02 μm .

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6.5 Sample Cleaning and Etching

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, use Murakumi reagent (10 g $K_3[Fe(CN)_6]$ + 10 g KOH + 100 mL H_2O) to gently etch for 5-10 s to enhance the defect contrast.

Wash and dry again and store in a dryer.

7 Assessment steps

7.1 Equipment Calibration

Calibrate the magnification of the metallographic microscope with a deviation of $<\pm 1\%$.

Calibrate the lighting system to ensure uniform light source without color difference.

7.2 Test conditions

Ambient temperature: $10^{\circ}C$ to $35^{\circ}C$, $20\pm 2^{\circ}C$ recommended.

Relative humidity: 30%-70%, $50\pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Microscopic observation

Place the sample on the stage of the metallographic microscope, adjust the focus, and select $200\times$ magnification.

Observe the sample surface in at least 5 fields of view with a field area of approximately 0.5 mm^2 . Bright field was used to observe pores and inclusions, and polarized light was used to observe free carbon and η phase.

7.4 Defect Assessment

Porosity Assessment:

Type A pores ($<10\text{ }\mu\text{m}$)

A00 (no pores), A02 ($<10\text{ pcs/mm}^2$), A04 ($10\text{--}20\text{ pcs/mm}^2$), A06 ($20\text{--}30\text{ pcs/mm}^2$), A08 ($>30\text{ pcs/mm}^2$).

Type B pores ($10\text{--}25\text{ }\mu\text{m}$)

B00 (no pores), B02 ($<5\text{ pcs/mm}^2$), B04 ($5\text{--}10\text{ pcs/mm}^2$), B06 ($10\text{--}15\text{ pcs/mm}^2$), B08 ($>15\text{ pcs/mm}^2$).

Inclusion Assessment

I00 (no inclusions), I02 ($<5\text{ pieces/mm}^2$, $<10\text{ }\mu\text{m}$), I04 ($5\text{--}10\text{ pieces/mm}^2$, $10\text{--}20\text{ }\mu\text{m}$), I06 ($>10\text{ pieces/mm}^2$, $>20\text{ }\mu\text{m}$).

Free Carbon Assessment

C00 (no free carbon), C02 ($<0.5\%$), C04 ($0.5\%\text{--}1.0\%$), C06 ($1.0\%\text{--}1.5\%$), C08 ($>1.5\%$).

η phase assessment

eta00 (no eta phase), eta02 ($<0.5\%$), eta04 ($0.5\%\text{--}1.0\%$), eta06 ($1.0\%\text{--}1.5\%$), eta08 ($>1.5\%$).

7.5 Result calculation

Record the defect levels of 5 fields of view, calculate the average value, and determine the final defect level of the sample.

Deviation assessment: The grade deviation of the 5 visual fields is $<\pm 1$ level, otherwise re-

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observation is required.

8 Evaluation of evaluation results

8.1 Defect grade range

The level of cemented carbide defects depends on the grade and purpose:

YG6 (6% Co): A02-B02-I02-C02- η 02, suitable for mining drill bits.

YG8 (8% Co): A04-B04-I02-C04- η 02, suitable for cutting tools.

YT15 (5% Co + TiC): A02-B02-I04-C02- η 04, suitable for finishing tools.

8.2 Deviation Assessment

of 3-5 samples is $\leq \pm 1$ level, otherwise retesting is required.

If the defect level exceeds the technical requirements, the cause needs to be analyzed (such as abnormal sintering process).

8.3 Analysis of influencing factors

Porosity: Insufficient sintering vacuum (< 10 Pa) or excessive cooling rate ($> 50^\circ\text{C}/\text{min}$) leads to increased porosity ($> \text{A04}$).

Inclusions: Low raw material purity (impurities $> 0.1\%$) or uneven mixing leads to increased inclusions ($> \text{I04}$).

Free carbon: Excessive carbon content ($> 0.2\%$) or uneven distribution leads to increased free carbon ($> \text{C04}$).

η phase: Insufficient carbon content ($< 0.1\%$) or high sintering temperature ($> 1450^\circ\text{C}$) leads to the formation of η phase ($> \eta 04$).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, magnification ($200\times$), observation method, ambient temperature (10°C to 35°C), humidity (30%-70%).

Test results: defect grade (A, B, I, C, η), mean value and deviation for each field of view.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Normative Appendix) Standard Defect Atlas

Type A pores: A00-A08, the spectrum shows the distribution of pores with a diameter of $< 10\ \mu\text{m}$.

Type B pores: B00-B08, the spectrum shows the distribution of pores with a diameter of $10\text{-}25\ \mu\text{m}$.

Inclusions: I00-I06, the graph shows the size and quantity of inclusions.

Free carbon: C00-C08, the graph shows the area percentage of free carbon.

η phase: $\eta 00\text{-}\eta 08$, the spectrum shows the area ratio of η phase.

Appendix B (Informative Appendix) Reference Values of Typical Cemented Carbide Defect

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Levels

Brand	Co content (wt %)	Defect level	Typical Applications
YG6	6	A02-B02-I02-C02-η02	Mining drill bits
YG8	8	A04-B04-I02-C04-η02	Cutting Tools
YT15	5	A02-B02-I04-C02-η04	Finishing tools

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

ISO 4499-3:2016 "Cemented Carbide - Microstructure Examination Part 3: Evaluation of Porosity, Inclusions, Free Carbon and η Phase" provides an international standardized procedure for the evaluation of cemented carbide microstructure defects, ensuring the accuracy and comparability of the results through metallographic microscope observation and standard atlas grading. The implementation of this standard helps cemented carbide quality control and provides technical support for high-performance application fields such as cutting tools and mining drills.

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appendix:

ISO 4499-2:2008 Cemented Carbide

— Microstructure inspection

Part 2: Methods for determination of grain size

1 Scope

This standard specifies the method for determining the grain size of tungsten carbide (WC) in cemented carbide microstructures, using a metallographic microscope combined with a linear section method or a planned section method for determination. This standard applies to cemented carbides with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbides with other carbides (such as TaC, TiC, NbC). This standard does not apply to non-cobalt-based cemented carbides or other non-cemented carbide materials.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 4499-1:2006 Cemented carbide — Microstructure examination Part 1: General guidance

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:1983 Cemented carbide terminology

3 Terms and definitions

This standard adopts ISO 3850:1983 and the following terms and definitions:

Grain size: The average diameter of tungsten carbide (WC) grains in cemented carbide, usually measured in microns (μm).

Linear cross-section method: The average grain size is calculated by measuring the cross-section diameter of the WC grains on a straight line in the microscope field of view.

Planned section method: The average grain size is calculated by measuring the cross-sectional area of multiple WC grains in the microscope field of view.

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4. Determination principle

The determination of WC carbide grain size is based on metallographic microscope observation, combined with linear section method or planned section method. The linear section method measures the cross-sectional diameter of the grains on a straight line in the microscope field of view and calculates the average value statistically; the planned section method measures the cross-sectional area of the grains and estimates the average grain size in combination with a geometric model. Both methods require the preparation of high-quality specimens to ensure that the surface is flat and free of contamination, in accordance with the general guidelines provided by ISO 4499-1:2006.

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5. Measurement equipment

5.1 Metallographic microscope

Magnification: 200×, 500×, 1000×, 500× is recommended for grain size determination.

Equipped with polarized light and differential interference contrast (DIC) capabilities for distinguishing WC grain boundaries.

Resolution: <0.2 μm .

5.2 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width <0.5 mm, equipped with cooling system.

Mounting machine: hot press mounting, temperature <150°C, pressure 20-30 MPa.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

Ultrasonic cleaner: frequency 40 kHz, used to clean samples.

5.3 Measurement tools

Microscope eyepiece micrometer: graduation value 0.01 mm, accuracy ±0.001 mm.

Image analysis software: supports grain boundary recognition and area calculation with an accuracy of ±0.1 μm .

5.4 Environmental Control

Temperature: 10°C to 35°C, 20±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size: 10×10× 5 mm.

The surface of the specimen should be flat and free of cracks, scratches or oxide layers.

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large (>0.5 μm), the number of samples needs to be increased to 5 .

6.3 Specimen cutting and mounting

The specimens were cut using a low-speed precision cutting machine with a cut width of <0.5 mm and ethanol or water as the coolant.

Hot press mounting, temperature <150°C, pressure 20-30 MPa, time 5-10 min.

6.4 Grinding and polishing of specimens

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Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness $R_a < 0.1 \mu\text{m}$.

Polishing: Use $0.25 \mu\text{m}$ aluminum oxide polishing paste, polishing cloth speed 300 r/min, surface roughness $R_a < 0.02 \mu\text{m}$.

6.5 Sample Cleaning and Etching

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, the surface was lightly etched using Murakumi reagent ($10 \text{ g K}_3[\text{Fe}(\text{CN})_6] + 10 \text{ g KOH} + 100 \text{ mL H}_2\text{O}$) for 5–10 s to enhance the contrast of the WC grain boundaries.

Wash and dry, store in a desiccator.

7 Measurement steps

7.1 Equipment Calibration

Calibrate the magnification of the metallographic microscope with a deviation of $< \pm 1\%$.

Calibrate the eyepiece micrometer or image analysis software to an accuracy of $\pm 0.1 \mu\text{m}$.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 2^\circ\text{C}$ recommended.

Relative humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Grain size determination

Linear Section Method:

Draw 3-5 parallel straight lines in the microscope field of view with a total length of $\geq 500 \mu\text{m}$.

The cross-sectional diameter of the WC grains on each straight line was measured, and 100-200 grains were counted.

Calculate the average grain size:

$$d = \frac{\sum d_i}{n}$$

Where d_i is the diameter of a single grain and n is the number of grains.

Planned cross-section method:

Five areas were randomly selected in the microscope field of view, and the cross-sectional areas of 100-200 grains were measured.

Use image analysis software to calculate the average area and convert it into equivalent diameter:

$$d = \sqrt{\frac{4A}{\pi}}$$

Among them A is the cross-sectional area of the grain.

The average grain size of each sample was recorded with a deviation of $< \pm 0.2 \mu\text{m}$.

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7.4 Calculation of results

Take the average grain size of 3-5 samples and calculate the standard deviation:

$$\sigma = \sqrt{\frac{\sum (d_i - \bar{d})^2}{n-1}}$$

Qualification judgment: average grain size deviation $< \pm 0.5 \mu\text{m}$, standard deviation $< 0.3 \mu\text{m}$.

8 Evaluation of measurement results

8.1 Grain size range

Cemented carbide WC grain size range depends on the grade:

YG6 (6% Co): $0.8-1.2 \mu\text{m}$, suitable for high toughness tools.

YG8 (8% Co): $1.0-1.5 \mu\text{m}$, suitable for cutting.

YT15 (5% Co + TiC): $0.6-1.0 \mu\text{m}$, suitable for finishing tools.

8.2 Deviation Assessment

of 3-5 samples is $< \pm 0.5 \mu\text{m}$, otherwise retesting is required.

If the grain size exceeds the technical requirements, the reasons need to be analyzed (such as uneven raw material particle size, excessive sintering temperature).

8.3 Analysis of influencing factors

Raw material particle size: WC raw material particle size $> 2 \mu\text{m}$ may result in larger grain size ($> 1.5 \mu\text{m}$).

Sintering temperature: Temperature $> 1450^\circ\text{C}$ or holding time $> 1 \text{ h}$ may result in grain growth ($> 0.5 \mu\text{m}$).

Cooling rate: Cooling rates $< 20^\circ\text{C}/\text{min}$ may result in grain coarsening ($> 0.3 \mu\text{m}$).

Co content: Co content fluctuation $> \pm 0.5\%$ may affect grain growth uniformity.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, magnification ($500\times$), measurement method (linear or planned), ambient temperature (10°C to 35°C), humidity (30%-70%).

Test results: grain size, mean, standard deviation and variation for each specimen.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference values of typical cemented carbide grain sizes

Brand	Co content (wt %)	Grain size (μm)	Typical Applications
YG6	6	0.8-1.2	Mining drill bits
YG8	8	1.0-1.5	Cutting Tools

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Brand	Co content (wt %)	Grain size (μm)	Typical Applications
YT15	5	0.6-1.0	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

ISO 4499-2:2008 "Cemented Carbide - Microstructure Examination Part 2: Grain Size Determination Method" provides an international standardized procedure for the determination of cemented carbide WC grain size, and ensures the accuracy and comparability of the measurement results through the linear section method or the planned section method. The implementation of this standard helps to optimize the performance of cemented carbide materials and provide technical support for high-performance application fields such as cutting tools and mining drills.

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appendix:

ISO 4499-1:2006 Cemented Carbide — Microstructure inspection Part 1: General guidelines

1 Scope

This standard provides general guidelines for the microstructure inspection of cemented carbide, including the basic principles of sample preparation, microscopic observation methods and defect assessment. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC). This standard is the basis of the ISO 4499 series of standards, and detailed measurement methods (such as grain size, defect assessment) are specified in subsequent parts (such as ISO 4499-2).

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3847:2005 Methods for preparation of cemented carbide specimens

ISO 3850:1983 Cemented carbide terminology

3 Terms and definitions

This standard adopts ISO 3850:1983 and the following terms and definitions:

Microstructure: The microstructure of cemented carbide under magnified observation, including WC grains, Co bonding phase and defects.

Defects: Abnormal features in the microstructure such as pores, inclusions, free carbon and eta phase.

Metallographic specimen: Cemented carbide sample prepared for microscopic observation by cutting, grinding, polishing and etching.

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4 Inspection Principle

The microstructure inspection of cemented carbide is based on metallographic microscopy observation, combined with sample preparation and appropriate etching technology to reveal the distribution and morphology of WC grains, Co phases and defects. The inspection process includes sample preparation, microscopic observation and result recording, following standardized procedures to ensure the reproducibility and comparability of the results. Specific methods such as defect assessment and grain size determination are detailed in subsequent standards.

5. Inspection Equipment

5.1 Metallographic microscope

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Magnification: 50×, 100×, 200×, 500×, 200× is recommended for routine observation.

Equipped with brightfield, darkfield and polarized light capabilities for distinguishing different phases and defects.

Resolution: <0.5 μm .

5.2 Sample preparation equipment

Cutting machine: low speed precision cutting, cut width <0.5 mm, equipped with cooling system.

Mounting machine: hot press mounting, temperature <150°C, pressure 20-30 MPa.

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

Ultrasonic cleaner: frequency 40 kHz, used to clean samples.

5.3 Measurement tools

Vernier caliper: accuracy ±0.02 mm, used to measure sample size.

Eyepiece micrometer: graduation value 0.01 mm, accuracy ±0.001 mm.

5.4 Environmental Control

Temperature: 10°C to 35°C, 20±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size: 10×10× 5 mm.

The surface of the specimen should be flat and free of cracks, scratches or oxide layers.

The specimens shall be prepared in accordance with ISO 3847:2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the results have large deviations, the number of samples needs to be increased to 5 .

6.3 Specimen cutting and mounting

The specimens were cut using a low-speed precision cutter with a cut width of <0.5 mm and ethanol or water as the coolant.

Hot press mounting, temperature <150°C, pressure 20-30 MPa, time 5-10 min.

6.4 Grinding and polishing of specimens

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 2500# sandpaper, surface roughness Ra <0.1 μm .

Polishing: Use 0.25 μm aluminum oxide polishing paste, polishing cloth speed 300 r/min, surface roughness Ra <0.02 μm .

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6.5 Sample Cleaning and Etching

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, the surface was lightly etched using Murakumi reagent (10 g $K_3[Fe(CN)_6]$ + 10 g KOH + 100 mL H_2O) for 5–10 s to enhance the WC grains and phase contrast.

Wash and dry again and store in a dryer.

7 Inspection steps

7.1 Equipment Calibration

Calibrate the magnification of the metallographic microscope with a deviation of $<\pm 1\%$.

Calibrate the lighting system to ensure uniform light source without color difference.

7.2 Test conditions

Ambient temperature: 10°C to 35°C, 20±2°C recommended.

Relative humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

7.3 Microscopic observation

Place the sample on the stage of the metallographic microscope, adjust the focus, and select 200× magnification.

Observe the sample surface in at least 5 fields of view with a field area of approximately 0.5 mm². Bright field was used to observe the WC grains and Co phase, and polarized light was used to observe defects (such as free carbon).

7.4 Recording of results

The microstructural characteristics of each field of view, including WC grain size, Co phase distribution and defect types, were recorded.

Take micrographs (resolution ≥ 5 MP) for subsequent analysis and reporting.

8 Evaluation of test results

8.1 Range of microstructural characteristics

WC grain size: 0.5-2.0 μm (depending on the grade).

Co phase content: 5%-15% (weight percentage).

Defects: The levels of pores, inclusions, free carbon and η phase must meet the technical requirements (refer to ISO 4499-2).

8.2 Deviation Assessment

The consistency deviation of the microstructural characteristics of the 5 fields of view was $<\pm 10\%$, otherwise re-observation was required.

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If the microstructure exceeds the technical requirements, the reasons need to be analyzed (such as abnormal sintering process parameters).

8.3 Analysis of influencing factors

Specimen preparation: Insufficient polishing ($R_a > 0.1 \mu\text{m}$) or excessive etching may mask defects.

Observation conditions: Uneven light source or improper magnification may cause grain boundaries to be blurred.

Material composition: Co content fluctuations $> \pm 0.5\%$ or uncontrolled carbon content may affect the microstructure.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, magnification ($200\times$), observation method, ambient temperature (10°C to 35°C), humidity (30%-70%).

Test results: microstructural characterization, photographic records and preliminary defect observations.

Evaluation conclusion: whether it meets the preliminary technical requirements.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Microstructure Characteristics of Typical Cemented Carbides

Brand	Co content (wt %)	WC grain size (μm)	Typical Applications
YG6	6	0.8-1.2	Mining drill bits
YG8	8	1.0-1.5	Cutting Tools
YT15	5	0.6-1.0	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C , $20 \pm 2^\circ\text{C}$ recommended.

Humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $< 0.02 \text{ mm/m}$.

Summarize

ISO 4499-1:2006 "Cemented Carbide - Microstructure Inspection Part 1: General Guidelines" provides an international framework for cemented carbide microstructure inspection, ensuring the reproducibility and comparability of inspection results through standardized sample preparation and observation methods. The implementation of this standard lays the foundation for subsequent specific measurements (such as grain size, defect assessment), and supports cemented carbide material performance optimization and quality control.

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appendix:

**ISO 3847:2005 Cemented Carbide
Sample preparation method**

1 Scope

This standard specifies the preparation method of cemented carbide specimens, including cutting, inlaying, grinding, polishing and cleaning, and is suitable for subsequent performance testing (such as bending strength, hardness) or microstructure inspection. This standard is applicable to cemented carbides with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbides with other carbides (such as TaC, TiC, NbC). This standard does not apply to non-cobalt-based cemented carbides or other non-cemented carbide materials.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For the referenced documents with a date, the applicable version is the version of that date; for the referenced documents without a date, the latest version (including all amendments) shall apply to this standard.

ISO 3850:1983 Cemented carbide terminology

3 Terms and definitions

This standard adopts ISO 3850:1983 and the following terms and definitions:

Test specimen: A sample of cemented carbide prepared by cutting and machining for performance testing or microscopic observation.

Mounting: Embed the specimen in resin or metal material to facilitate subsequent grinding, polishing and observation.

Grinding and polishing: Remove surface defects of the sample by grinding and polishing to obtain a smooth surface.

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4 Preparation principle

The preparation of cemented carbide specimens aims to obtain a flat, undamaged surface suitable for subsequent testing or microscopic observation. The preparation process includes cutting the specimen to obtain the appropriate size, mounting to protect the edges, grinding and polishing to remove surface defects, and cleaning to remove residues. The preparation method needs to ensure that the specimen does not undergo microstructural changes due to thermal or mechanical stress.

5. Preparation equipment

5.1 Cutting equipment

Low-speed precision cutting machine: cut width < 0.5 mm, equipped with cooling system (such as water or ethanol).

Cutting wheel: particle size 120-240#, thickness 0.5-1.0 mm.

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5.2 Mounting equipment

Hot press mounting machine: temperature $<150^{\circ}\text{C}$, pressure 20-30 MPa, time 5-10 min.

Resin or metal inlay materials: thermoplastic resins (such as phenolic resins) or low melting point metals (such as tin-lead alloys).

5.3 Grinding and polishing equipment

Grinding and polishing machine: speed 300-600 r/min, equipped with 600#, 1200#, 2500# diamond sandpaper and polishing cloth.

Polishing liquid: $0.25\text{ }\mu\text{m}$ alumina suspension or $1\text{ }\mu\text{m}$ diamond polishing paste.

5.4 Cleaning equipment

Ultrasonic cleaner: frequency 40 kHz, power 100-200 W.

Cleaning agent: anhydrous ethanol or acetone.

5.5 Environmental Control

Temperature: 10°C to 35°C , $20\pm 2^{\circ}\text{C}$ recommended.

Humidity: 30%-70%, $50\pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size is $10\times 10\times 5\text{ mm}$ or 10 mm in diameter and 5 mm in height.

There should be no obvious cracks, burns or oxide layers on the surface of the specimen.

The test specimens should be representative of the homogeneity of the material batch.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness. If subsequent tests require higher accuracy, the number needs to be increased to 5.

6.3 Specimen cutting

The specimens were cut using a low-speed precision cutting machine with a cutting speed of $<0.1\text{ mm/s}$ and ethanol or water as the coolant.

The cutting direction is perpendicular to the material lamination surface, and the cut width is $<0.5\text{ mm}$.

6.4 Specimen mounting

The sample is placed in an inlay mold and thermoplastic resin or low melting point metal is added. Hot press mounting, temperature $<150^{\circ}\text{C}$, pressure 20-30 MPa, time 5-10 min, ensure the specimen edge is intact.

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6.5 Grinding and polishing of specimens

Rough grinding: Use 600# or 1200# diamond sandpaper to gradually remove the cutting marks and apply a pressure of 5-10 N.

Fine grinding: Use 2500# sandpaper, surface roughness $R_a < 0.1 \mu\text{m}$.

Polishing: Use $0.25 \mu\text{m}$ alumina polishing liquid, polishing cloth speed 300 r/min, surface roughness $R_a < 0.02 \mu\text{m}$, polishing time 5-10 min.

6.6 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Preparation steps

7.1 Equipment Calibration

Calibrate the cutting machine speed, the deviation is $< \pm 5\%$.

Calibrate the grinding and polishing machine speed and pressure, with a deviation of $< \pm 2\%$.

Check mounting machine temperature and pressure, deviation $< \pm 1^\circ\text{C}$ and $\pm 1 \text{ MPa}$.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 2^\circ\text{C}$ recommended.

Relative humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Operation Process

Complete the sample cutting, mounting, grinding, polishing and cleaning in the order of Sections 6.3-6.6.

After each step, check the surface quality of the specimen and record any abnormalities (such as cracks, burns).

7.4 Result Check

Surface roughness: $R_a < 0.02 \mu\text{m}$.

Surface flatness: Deviation $< 0.01 \text{ mm}$.

No visible scratches or contamination.

8 Evaluation of preparation results

8.1 Surface quality range

There should be no visible cracks, burns or oxide layers on the surface of the specimen.

Roughness $R_a < 0.02 \mu\text{m}$, flatness deviation $< 0.01 \text{ mm}$.

8.2 Deviation Assessment

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of 3-5 samples is $\leq \pm 10\%$, otherwise re-preparation is required.

If the surface quality does not meet the requirements, the reasons need to be analyzed (such as cutting speed is too high, polishing time is insufficient).

8.3 Analysis of influencing factors

Cutting: Cutting speeds > 0.1 mm/s or insufficient cooling may cause cracks (> 0.05 mm).

Mounting: Temperatures $> 150^{\circ}\text{C}$ or pressures < 20 MPa may cause specimen deformation (> 0.1 mm).

Grinding and polishing: Sandpaper with too coarse grain ($< 600\#$) or polishing time < 5 min may result in surface roughness ($R_a > 0.1$ μm).

Cleaning: Cleaning agent residues or insufficient drying may cause contamination (visible particles > 0.01 mm).

9. Prepare report

The report should include the following:

Sample information: brand, batch number, initial size.

Preparation conditions: equipment model, cutting speed (< 0.1 mm/s), mounting temperature ($< 150^{\circ}\text{C}$), grinding and polishing parameters, ambient temperature (10°C to 35°C), humidity (30%-70%).

Preparation results: surface roughness ($R_a < 0.02$ μm), flatness deviation (< 0.01 mm), abnormal records.

Evaluation conclusion: whether it meets the requirements of subsequent tests.

Preparation date and operator's signature.

Appendix A (Informative Appendix) Reference values of typical cemented carbide specimen preparation parameters

Brand	Co content (wt %)	Sample size (mm)	Surface roughness (R_a , μm)	Typical Applications
YG6	6	10×10×5	< 0.02	Mining drill bits
YG8	8	10×10×5	< 0.02	Cutting Tools
YT15	5	10×10×5	< 0.02	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C , $20 \pm 2^{\circ}\text{C}$ recommended.

Humidity: 30%-70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation < 0.02 mm/m.

Summarize

ISO 3847:2005 "Methods for Preparation of Cemented Carbide Samples" provides an international standardized procedure for the preparation of cemented carbide samples. Through standardized cutting, mounting, grinding, polishing and cleaning steps, it ensures that the surface quality of the

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sample meets the requirements of subsequent performance testing or microstructure inspection. The implementation of this standard provides a reliable technical basis for the performance evaluation and quality control of cemented carbide materials.

appendix:

ISO 3850:2018 Cemented Carbide
the term

1 Scope

This standard defines the terms and definitions of cemented carbide and related materials, covering material composition, preparation process, microstructure, performance testing and application areas. This standard applies to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co), nickel (Ni) or iron (Fe) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, NbC, VC). This standard is the basis of cemented carbide standardization series (such as ISO 4499, ISO 3847) and is suitable for international trade, research and industrial applications.

2 Normative references

This standard does not directly reference other standards, but as part of the cemented carbide standardization series, it is related to the following standards:

ISO 4499-1:2006 Cemented carbide — Microstructure examination Part 1: General guidance

ISO 3847:2005 Methods for preparation of cemented carbide specimens

Note: The latest versions of referenced documents (including all amendments) apply to this standard.

3 Terms and definitions

The following are carbide-related terms defined in ISO 3850:2018, categorized by category:

3.1 Material composition

3.1.1 Hard phase

Tungsten carbide (WC): Carbide, the main hard component in cemented carbide, has the chemical formula WC and has high hardness and wear resistance.

Other carbides: such as tantalum carbide (TaC), titanium carbide (TiC), niobium carbide (NbC), and vanadium carbide (VC), are used as auxiliary components of the hard phase.

3.1.2 Bonding phase

Cobalt (Co): A common bonding metal in cemented carbide, with a phase content of usually 5%-15% (by weight), providing toughness and bonding strength.

Nickel (Ni): As a metal that replaces the bonding phase, it is suitable for corrosion-resistant environments.

Iron (Fe): A bonding phase component present in small amounts and often used as an alloying element.

3.1.3 Impurities

Free carbon: Carbon that does not form compounds with metals and exists in the form of graphite.

η phase: A brittle phase formed due to insufficient carbon content, such as W_3Co_3C or Co_6W_6C .

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3.2 Preparation process

3.2.1 Powder Metallurgy

The manufacturing process of cemented carbide is prepared by mixing, pressing and sintering powders.

3.2.2 Sintering

The process of combining powder particles at high temperature (1300°C-1500°C) can be divided into vacuum sintering and low temperature sintering.

3.2.3 Hot Isostatic Pressing (HIP)

Subsequent treatment process to eliminate porosity at high temperature and pressure.

3.3 Microstructure

3.3.1 Grain

The microscopic particles of WC in cemented carbide are usually 0.5-5.0 μm in size .

3.3.2 Porosity

The pores or voids in the microstructure are divided into Type A (<10 μm) and Type B (10-25 μm).

3.3.3 Inclusions

Non-metallic impurities (such as oxides and sulfides) exist in the form of particles.

3.4 Performance Testing

3.4.1 Flexural strength

The maximum stress that the specimen can withstand in a three-point or four-point bending test, in MPa.

3.4.2 Hardness

The intrusion resistance of cemented carbide is usually expressed in Rockwell hardness (HRA) or Vickers hardness (HV).

3.4.3 Fracture toughness

The ability of a material to resist crack growth is expressed by the stress intensity factor K_{IC} K_{IC} , with the unit of $MPa \cdot m^{1/2}$.

3.5 Application Areas

3.5.1 Cutting tools

Carbide is used in cutting tools for machining metal, wood or composite materials.

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3.5.2 Wear-resistant parts

For example, mining drill bits and stamping dies rely on the high wear resistance of cemented carbide.

3.5.3 Military Applications

Cemented carbide is used to make armor-piercing cores or armor materials.

4 Principles of Terminology Use

Terminology should be consistent in relevant standards or technical documents to avoid ambiguity. Symbols and units follow the International System of Units (SI), such as μm (micrometer), MPa (megapascal).

Standard terms shall be used first when defining terms. If there are no corresponding definitions, industry practices may be used as a reference.

5 Terminology Examples

The following are some examples of how some of these terms are used in practice:

Grain size: The WC grain size of YG6 grade cemented carbide is 0.8-1.2 μm .

Sintering Temperature: The typical sintering temperature of YT15 grade cemented carbide is 1400°C-1450°C.

Bending strength: The bending strength of YG8 grade cemented carbide ranges from 1800-2200 MPa.

Appendix A (Informative Appendix) Typical cemented carbide terminology application reference values

Brand	Co content (wt %)	Grain size (μm)	Flexural strength(MPa)	Typical Applications
YG6	6	0.8-1.2	2000-2500	Mining drill bits
YG8	8	1.0-1.5	1800-2200	Cutting Tools
YT15	5	0.6-1.0	1300-1600	Finishing tools

Appendix B (Informative Appendix) Terminology Development History

ISO 3850 was first published in 1983 and mainly defines the basic terms of cemented carbide.

The 2018 revision updated the definition of the bonding phase (added Ni and Fe), added military application terms, and optimized the preparation process description.

Summarize

ISO 3850:2018 "Terminology for Cemented Carbide" provides a unified terminology basis for international standardization in the field of cemented carbide, covering material composition, preparation process, microstructure, performance testing and application areas. The implementation of this standard promotes technical exchanges and quality control in the global cemented carbide industry, and lays a language and conceptual foundation for the application of subsequent standards

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(such as ISO 4499 and ISO 3847).

appendix:

ISO 3850:2018 Hardmetal
— Vocabulary

1 Scope

This International Standard defines terms and definitions related to hardmetals and their associated materials, covering material composition, manufacturing processes, microstructure, performance testing, and application fields. This standard applies to hardmetals with tungsten carbide (WC) as the primary hard phase and cobalt (Co), nickel (Ni), or iron (Fe) as the binder phase, including those with additional carbides (eg, TaC, TiC, NbC, VC). It serves as a foundational vocabulary for the hardmetal standardization series (eg, ISO 4499, ISO 3847) and is intended for use in international trade, research, and industrial applications.

2 Normative References

This standard does not directly reference other standards but is part of the hardmetal standardization series and is related to the following:

ISO 4499-1:2006 Hardmetals — Metallographic determination of microstructure — Part 1: General guidance

ISO 3847:2005 Hardmetals — Determination of sample preparation methods

Note: The latest versions of referenced documents (including amendments) apply.

3 Terms and Definitions

The following terms and definitions are defined in accordance with ISO 3850:2018, categorized by subject area:

3.1 Material Composition

3.1.1 Hard Phase

Tungsten Carbide (WC)

The primary hard component in hardmetals, with the chemical formula WC, characterized by high hardness and wear resistance.

Other Carbides

Such as tantalum carbide (TaC), titanium carbide (TiC), niobium carbide (NbC), and vanadium carbide (VC), used as auxiliary hard phases.

3.1.2 Binder Phase

Cobalt (Co)

The common binder metal in hardmetals, typically ranging from 5% to 15% by weight, provides toughness and bonding strength.

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Nickel (Ni)

An alternative binder metal, suitable for corrosion-resistant environments.

Iron (Fe)

A minor binder phase component, often used as an alloying element.

3.1.3 Impurities

Free Carbon

Carbon not combined with metals, existing in graphite form.

Eta Phase (η -phase)

A brittle phase formed due to carbon deficiency, such as W_3Co_3C or Co_6W_6C .

3.2 Manufacturing Processes

3.2.1 Powder Metallurgy

The manufacturing process for hardmetals, involving mixing, pressing, and sintering of powders.

3.2.2 Sintering

The process of bonding powder particles at high temperatures (1300°C to 1500°C), including vacuum sintering and low-temperature sintering.

3.2.3 Hot Isostatic Pressing (HIP)

A post-treatment process to eliminate porosity under high temperature and pressure.

3.3 Microstructure

3.3.1 Grain

Microscopic particles of WC in hardmetals, typically ranging from 0.5 to 5.0 μm in size.

3.3.2 Porosity

Gas pores or voids in the microstructure, classified as Type A ($<10 \mu m$) and Type B (10-25 μm).

3.3.3 Inclusions

Non-metallic impurities (eg, oxides, sulfides) present as particles in hardmetals.

3.4 Performance Testing

3.4.1 Transverse Rupture Strength

The maximum stress a specimen withstands in a three- or four-point bending test, measured in MPa.

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3.4.2 Hardness

The resistance of hardmetals to indentation, typically measured using Rockwell A (HRA) or Vickers (HV) scales.

3.4.3 Fracture Toughness:

The ability of a material to resist crack propagation, expressed as the stress intensity factor (K_{IC}), in units of $MPa \cdot m^{1/2}$.

3.5 Application Fields

3.5.1 Cutting Tools

Hardmetals used for machining metals, wood, or composites.

3.5.2 Wear Parts

Such as mining drill bits and stamping dies, relying on the high wear resistance of hardmetals .

3.5.3 Military Applications

Hardmetals used in armor-piercing projectiles or armor materials.

4 Principles of Terminology Usage

Terms shall be used consistently within relevant standards or technical documents to avoid ambiguity.

Symbols and units shall conform to the International System of Units (SI), eg, μm (micrometers), MPa (megapascals).

Where no standard definition exists, industry conventions may be referenced.

5 Examples of Terminology Usage

The following are examples of terms in practical applications:

Grain Size

The WC grain size in YG6 hardmetal ranges from 0.8 to 1.2 μm .

Sintering Temperature

The typical sintering temperature for YT15 hardmetal ranges from 1400°C to 1450°C.

Transverse Rupture Strength

The transverse rupture strength of YG8 hardmetal ranges from 1800 to 2200 MPa.

Annex A (Informative) Typical Hardmetal Terminology Application Reference Values

Grade	Co Content (wt %)	Grain Size (μm)	Transverse Rupture Strength (MPa)	Typical Application

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YG6	6	0.8-1.2	2000-2500	Mining drill bits
YG8	8	1.0-1.5	1800-2200	Cutting tools
YT15	5	0.6-1.0	1300-1600	Precision cutting tools

Annex B (Informative) Historical Development of Terminology

ISO 3850 was first published in 1983, primarily defining basic hardmetal terminology.

The 2018 revision updated binder phase definitions (adding Ni and Fe), introduced military application terms, and refined manufacturing process descriptions.

Summary

ISO 3850:2018 "Hardmetal — Vocabulary" provides a standardized terminology foundation for the hardmetal industry, covering material composition, manufacturing processes, microstructure, performance testing, and application fields. Its implementation facilitates global technical communication and quality control, supporting subsequent standards such as ISO 4499 and ISO 3847.

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appendix:

GB/T 4295-2008 Cemented Carbide
Microstructure defect assessment method

1 Scope

This standard specifies the evaluation method of microstructural defects in cemented carbide, including the observation and evaluation procedures of defects such as pores, inclusions, free carbon and η phase, using metallographic microscope observation. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, including cemented carbide with other carbides (such as TaC, TiC, VC). This standard does not apply to non-cobalt-based cemented carbide or other composite materials.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

GB/T 3847-2005 Method for preparation of cemented carbide specimens

GB/T 3850-1983 Terminology of cemented carbide

GB/T 3489-2005 Method for evaluating the metallographic structure of cemented carbide

GB/T 3848-2001 Method for determination of density of cemented carbide

3 Terms and definitions

This standard adopts GB/T 3850-1983 and the following terms and definitions:

Porosity : Pores or voids in the microstructure of cemented carbide, divided into Type A (diameter $<10\ \mu\text{m}$) and Type B (diameter $10\text{--}25\ \mu\text{m}$).

Inclusions : Non-metallic impurities (such as oxides and sulfides) in cemented carbide, usually in the form of particles.

Free carbon : Carbon in cemented carbide that does not form compounds with metals, exists in the form of graphite, codenamed C.

η phase : A brittle phase formed in cemented carbide due to insufficient carbon content (such as $\text{W}_3\text{Co}_3\text{C}$), codenamed η .

Cemented carbide : A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

4 Assessment Principles

The evaluation of cemented carbide microstructure defects adopts metallographic microscope observation method, and the types and degrees of pores, inclusions, free carbon and η phase are evaluated by preparing samples, polishing, microscopic observation and comparing with standard atlases. The defect evaluation and classification are based on the size, number and distribution of defects, and the standard atlas (Appendix A) is used for comparison to quantitatively or qualitatively describe the defect level.

5. Assessment equipment

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5.1 Metallographic microscope

Magnification: 100×, 200×, 500×, 200× is recommended for routine observation.

Equipped with polarized light function to distinguish between free carbon and η phase.

Resolution: $<0.5\ \mu\text{m}$.

5.2 Sample preparation equipment

Cutting machine: low speed precision cutting, incision width $<0.5\ \text{mm}$.

Mounting machine: hot press mounting, temperature $<150^\circ\text{C}$, to avoid structural changes.

Grinding and polishing machine: speed 300-600 r/min, equipped with diamond sandpaper and polishing cloth.

Ultrasonic cleaner: frequency 40 kHz, used to clean samples.

5.3 Auxiliary equipment

Vernier caliper: accuracy $\pm 0.02\ \text{mm}$, used to measure sample size.

Microhardness tester: optional, used to assist in the analysis of η phase hardness ($>\text{HRC } 70$).

5.4 Environmental Control

Temperature: 10°C to 35°C , $20\pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, $50\pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Sample shape: rectangular or cylindrical, recommended size: $10\times 10\times 5\ \text{mm}$.

The surface of the specimen should be flat and free of cracks or oxide layer.

The specimens should comply with the preparation requirements of GB/T 3847-2005.

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large (>1 level), the number of samples needs to be increased to 5.

6.3 Specimen cutting and mounting

The specimens were cut using a low-speed precision cutting machine with a cut width of $<0.5\ \text{mm}$ and water as the coolant.

Hot press mounting, temperature $<150^\circ\text{C}$, pressure 20-30 MPa, time 5-10 min.

6.4 Grinding and polishing of specimens

Rough grinding: Use 120#, 240#, 600# diamond sandpaper to gradually remove cutting marks.

Fine grinding: Use 1000#, 1500# sandpaper, surface roughness $R_a < 0.2\ \mu\text{m}$.

Polishing: Use $1\ \mu\text{m}$ diamond polishing paste, polishing cloth speed 300 r/min, surface roughness

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Ra <0.05 μm .

6.5 Sample cleaning

Clean the sample surface with anhydrous ethanol or acetone and perform ultrasonic cleaning for 5 min (frequency 40 kHz).

After drying, store in a desiccator to avoid oxidation or contamination.

7 Assessment steps

7.1 Equipment Calibration

Calibrate the magnification of the metallographic microscope with a deviation of $<\pm 1\%$.

Check the lighting system to ensure that the light source is uniform and without color difference.

7.2 Test conditions

Ambient temperature: 10°C to 35°C, 20 $\pm$ 5°C recommended.

Relative humidity: 30%-80%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

7.3 Microscopic observation

Place the sample on the stage of the metallographic microscope, adjust the focus, and select 200 $\times$ magnification.

Observe the sample surface in at least 5 fields of view with a field area of approximately 0.5 mm² .
Record the distribution and morphology of pores, inclusions, free carbon and eta phase and compare with the standard spectrum (Appendix A).

7.4 Defect Assessment

Porosity Assessment :

Type A pores (<10 μm):

Rating by quantity: A00 (no pores), A02 (<10 pcs / mm²), A04 (10-20 pcs/mm²) , A06 (20-30 pcs/mm²) , A08 (>30 pcs/mm²) .

Type B pores (10-25 μm):

Rating by quantity: B00 (no pores), B02 (<5 pcs /mm²) , B04 (5-10 pcs/mm²) , B06 (10-15 pcs/mm²) , B08 (>15 pcs/mm²) .

Inclusion Assessment :

Graded by number and size: I00 (no inclusions), I02 (<5 pieces / mm² , <10 μm) , I04 (5-10 pieces/mm² , 10-20 μm) , I06 (>10 pieces/mm² , >20 μm) .

Free Carbon Assessment :

Rated by area percentage: C00 (no free carbon), C02 (<0.5%), C04 (0.5%-1.0%), C06 (1.0%-1.5%), and C08 (>1.5%) .

η phase assessment :

Rating by area percentage: η 00 (no η phase), η 02 (<0.5%), η 04 (0.5%-1.0%), η 06 (1.0%-1.5%), and η 08 (>1.5%).

7.5 Results Recording

Record the defect rating for each field of view and calculate the average to determine the final defect grade of the specimen.

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Deviation assessment: The grade deviation of the 5 visual fields is $<\pm 1$ level, otherwise re-observation is required.

8 Evaluation of evaluation results

8.1 Defect level range

The level of microstructural defects in cemented carbide depends on the grade and purpose:

YG6 (6% Co): A02-B02-I02-C02- η 02, suitable for mining drill bits.

YG8 (8% Co): A04-B04-I02-C04- η 02, suitable for cutting tools.

YT15 (5% Co + TiC): A02-B02-I04-C02- η 04, suitable for finishing tools.

8.2 Deviation Assessment

the 5 fields of view is $<\pm 1$ grade, otherwise retesting is required.

If the defect level exceeds the technical requirements, the cause needs to be analyzed (such as sintering temperature is too high, carbon content is out of control).

8.3 Analysis of influencing factors

Porosity: Insufficient sintering vacuum (<10 Pa) will lead to increased porosity ($>A04$).

Inclusions: Low raw material purity (impurities $> 0.1\%$) will lead to an increase in inclusions ($> I04$).

Free Carbon: Too high carbon content ($>0.2\%$) will lead to increased free carbon ($>C04$).

η phase: Insufficient carbon content ($<0.1\%$) or excessive cooling rate ($>50^\circ\text{C}/\text{min}$) will lead to the formation of η phase ($>\eta 04$).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size.

Test conditions: equipment model, magnification ($200\times$), ambient temperature (10°C to 35°C), humidity (30%-80%).

Test results: defect rating (A, B, I, C, η), mean and deviation for each field of view.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator's signature.

Appendix A (Normative Appendix) Standard Defect Atlas

Type A pores: A00-A08, the spectrum shows the distribution of pores with a diameter of $<10\ \mu\text{m}$.

Type B pores: B00-B08, the spectrum shows the distribution of pores with a diameter of $10\text{-}25\ \mu\text{m}$.

Inclusions: I00-I06, the graph shows the size and quantity of inclusions.

Free carbon: C00-C08, the graph shows the area percentage of free carbon.

η phase: $\eta 00\text{-}\eta 08$, the spectrum shows the area ratio of η phase.

Appendix B (Informative Appendix) Reference Values of Typical Cemented Carbide Defect Levels

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Brand	Co content (wt %)	Defect level	Typical Applications
YG6	6	A02-B02-I02-C02-η02	Mining drill bits
YG8	8	A04-B04-I02-C04-η02	Cutting Tools
YT15	5	A02-B02-I04-C02-η04	Finishing tools

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

GB/T 4295-2008 "Method for evaluating microstructure defects in cemented carbide" provides a standardized procedure for evaluating microstructure defects in cemented carbide, and ensures the accuracy and repeatability of the evaluation results through metallographic microscope observation. The implementation of this standard helps the quality control of cemented carbide materials and provides reliable technical support for high-performance application fields such as cutting tools and mining drills.

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appendix:

GB/T 5249-2008

Cemented Carbide

General Specifications for Sample Preparation

1 Scope

This standard specifies the general specifications for the preparation of cemented carbide samples, including the steps of sample sampling, cutting, inlaying, grinding, polishing, cleaning, etc. It is applicable to the sample preparation for cemented carbide performance testing (such as hardness, density, bending strength, fracture toughness, microstructure, etc.). This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and also to cemented carbide with other carbides (such as TaC, TiC, VC). This standard is not applicable to the preparation of coated cemented carbide or cemented carbide samples after surface strengthening.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For all referenced documents with dates, all subsequent amendments (excluding errata) or revisions are not applicable to this standard. For all referenced documents without dates, the latest version is applicable to this standard.

GB/T 18376-2001 Cemented carbide performance test method

GB/T 3849-2008 Test method for Vickers hardness of cemented carbide

GB/T 7997-2010 Test method for fracture toughness of cemented carbide

GB/T 3488-2008 Cemented carbide microstructure test method

ISO 3878:1983 Cemented carbide — Specification for specimen preparation

3 Terms and definitions

This standard uses the following terms and definitions:

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

Test specimen: A representative portion taken from a cemented carbide product or blank for performance testing.

Grinding and polishing: Through mechanical grinding and polishing, the surface of the sample is made to reach a mirror state.

Surface roughness (Ra): The arithmetic mean deviation of the surface roughness of the specimen, in μm .

4. Sample collection

4.1 Sampling principles

The specimens should be taken from representative parts of the cemented carbide products or blanks to ensure that the performance test results are statistically significant.

The sampling location should avoid edges and defective areas (such as cracks and pore

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concentration areas).

4.2 Sampling quantity

The number of samples taken for each batch of products or blanks shall not be less than 3 , and for performance tests (such as hardness, fracture toughness) shall not be less than 5.

If the batch quantity is <10 pieces, the sampling ratio is 30%-50%; if the batch quantity is >100 pieces, the sampling ratio is 5%-10%.

4.3 Sampling Marking

The samples should be marked with batch number, brand number (such as YG8, YT15) and sampling location. The marking should not affect the subsequent processing or testing area.

5. Sample cutting

5.1 Equipment requirements

Cutting machine: equipped with diamond saw blade, cutting speed <500 r/min.

Coolant: distilled water or special coolant, temperature <40°C.

5.2 Cutting steps

Fix the carbide product or blank on the cutting machine workbench.

Cut with a diamond saw blade at a low speed (<500 r/min) and apply slight pressure (<50 N).

Keep cooling down and avoid local overheating (temperature < 60°C).

5.3 Cutting results

The specimen size should meet the requirements of subsequent tests, such as:

Hardness test: 5×5×2 mm (±0.1 mm).

Fracture toughness test: 20×4×2 mm (±0.02 mm).

Microstructure inspection: 10×10× 5 mm (±0.1 mm).

The cut surface should be smooth without obvious cracks or burn marks.

6. Specimen mounting

6.1 Scope of application

Mounting is required when the specimen is small (<5 mm) or has an irregular shape.

Mounting improves specimen handling and test surface stability.

6.2 Equipment requirements

Hot mounting machine: temperature range 150-180°C, pressure 20-30 MPa.

Mounting resin: Thermosetting resin or epoxy resin, hardness > HV 100.

6.3 Mounting steps

Place the specimen in a mounting mold and add resin powder or liquid resin.

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Set the temperature to 150-180°C, the pressure to 20-30 MPa, and heat for 5-10 min.
Cool naturally to room temperature (<40°C) and remove the mounted specimen.

6.4 Mosaic Results

The surface of the mounted specimen is flat, the resin is firmly bonded to the specimen, and there are no bubbles or cracks.

The test surface of the specimen is exposed, with an area > 5×5 mm.

7. Sample grinding and polishing

7.1 Equipment requirements

Grinding and polishing machine: speed 200-300 r/min.

Sandpaper: grit 400#-2000# (SiC sandpaper).

Polishing disc: equipped with diamond polishing liquid (particle size 0.5-1 μm).

7.2 Grinding and polishing steps

coarse grinding:

Use 400#-800# sandpaper to gradually remove the cutting marks at a speed of 200 r/min and apply slight pressure (<20 N).

After each change of sandpaper, rinse the specimen with water to remove grinding residue.

fine grinding:

Use 1000#-2000# sandpaper, gradually increase the grit, rotate at 200 r/min, and apply slight pressure (<10 N).

Ensure that there are no obvious scratches on the surface and the roughness is reduced to Ra <0.2 μm .

polishing:

Diamond polishing liquid (particle size 0.5 μm) was used, the polishing disk speed was 300 r/min, and slight pressure (<5 N) was applied.

Polished to mirror finish, surface roughness Ra <0.05 μm (microscope inspection).

7.3 Grinding and polishing results

The surface of the sample is flat and smooth, without scratches, cracks or burn marks.

The surface roughness Ra <0.05 μm meets the test requirements of hardness, fracture toughness, microstructure, etc.

8. Sample cleaning

8.1 Cleaning methods

Soak the specimen in anhydrous ethanol or acetone for 1-2 min to remove oil, dust and polishing residue.

Use an ultrasonic cleaner (frequency 40 kHz, power 100 W) for 2-3 min to enhance the cleaning effect.

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Use compressed air or filter paper to wipe the surface of the sample dry to avoid water stains.

8.2 Cleaning results

There is no visible dirt or residue on the surface of the sample and it is suitable for subsequent testing.

9. Sample inspection

9.1 Appearance inspection

Check whether the surface of the specimen is flat and free of cracks, pores or burn marks.

Measure the sample size and the deviation should meet the requirements in Table 1.

Table 1 Specimen size deviation requirements

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appendix:

GB/T 5249-2008
Cemented Carbide
General Specifications for Sample Preparation

1 Scope

This standard specifies the general specifications for the preparation of specimens for cemented carbide performance testing, including requirements for sampling, cutting, inlaying, grinding, polishing, cleaning, marking, etc. This standard is applicable to cemented carbides with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and also to cemented carbides with other carbides (such as TaC, TiC, VC). This standard is applicable to the preparation of specimens for performance tests such as hardness, density, bending strength, fracture toughness, and microstructure, but not to the preparation of specimens for coated cemented carbides or cemented carbides after surface strengthening.

2 Normative references

The clauses in the following documents become the clauses of this standard through reference in this standard. For all referenced documents with dates, all subsequent amendments (excluding errata) or revisions are not applicable to this standard. For all referenced documents without dates, the latest version is applicable to this standard.

GB/T 3849-2008 Test method for Vickers hardness of cemented carbide

GB/T 3488-2008 Cemented carbide microstructure test method

GB/T 7997-2010 Test method for fracture toughness of cemented carbide

GB/T 3850-2008 Determination method of flexural strength of cemented carbide

GB/T 3848-2008 Method for determination of density of cemented carbide

ISO 4489:1978 Methods for preparation and testing of cemented carbide specimens

3 Terms and definitions

This standard uses the following terms and definitions:

Cemented carbide: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

Test specimen: A sample taken from cemented carbide materials or products for performance testing.

Sampling: The process of extracting samples from cemented carbide materials or products.

Grinding and polishing: The process of making the surface of the sample reach the specified roughness through mechanical grinding and polishing.

Surface roughness (Ra): The arithmetic mean roughness of the sample surface, in μm .

4 Principle of sample preparation

The purpose of preparing cemented carbide specimens is to ensure that the surface of the specimens is flat and defect-free through sampling, cutting, mounting, grinding, polishing, cleaning and other steps to meet the accuracy requirements of performance testing. Specimen preparation should avoid introducing processing defects (such as cracks, overheating and structural changes) and ensure that

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the specimen size, surface roughness and geometry meet the requirements of the corresponding test standards.

5. Sample preparation equipment

5.1 Cutting equipment

Cutting machine: equipped with diamond saw blade, cutting speed 300-500 r/min.

Coolant: Water or water-based coolant, temperature controlled $<60^{\circ}\text{C}$, avoid overheating.

5.2 Mounting equipment

Hot mounting machine: temperature range $150\text{--}200^{\circ}\text{C}$, pressure 20-30 MPa.

Mounting material: phenolic resin or epoxy resin, temperature resistant $>150^{\circ}\text{C}$.

5.3 Grinding and polishing equipment

Grinding and polishing machine: speed 200-500 r/min.

Sandpaper: grit 400#-2000#.

Polishing disc: felt or flannel, speed 300-400 r/min.

Polishing agent: Diamond polishing liquid, particle size $0.5\text{--}1\text{ }\mu\text{m}$.

5.4 Cleaning equipment

Ultrasonic cleaner: frequency 40 kHz, power 100-200 W.

Cleaning fluid: anhydrous ethanol or acetone.

5.5 Measurement Tools

Vernier caliper: accuracy $\pm 0.02\text{ mm}$.

Digital micrometer: accuracy $\pm 0.001\text{ mm}$.

Surface roughness tester: accuracy $\pm 0.01\text{ }\mu\text{m}$.

5.6 Environmental Control

Temperature: $20\pm 5^{\circ}\text{C}$.

Humidity: $50\pm 10\%$.

No vibration, no corrosive gas environment.

6 Sample preparation steps

6.1 Sampling

6.1.1 Sampling location

Sampling should be representative of the overall material properties, avoiding areas close to edges, surface defects or heat affected zones.

For bars, plates or parts, the sampling location should comply with the corresponding test standards:

Hardness test: $>1\text{ mm}$ from the surface.

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Microstructure inspection: >0.5 mm from the surface.

Bending strength test: >2 mm from the edge.

6.1.2 Sampling quantity

The number of samples taken for each batch shall not be less than 5 to ensure statistical representativeness.

If the test result deviation is large (>5%), the number of samples needs to be increased to 10 .

6.1.3 Sampling method

Use a diamond saw blade for cutting, water as coolant, cutting speed of 300-500 r/min, temperature <60°C to avoid overheating leading to tissue changes.

The cutting surface should be flat with a verticality deviation of <0.05 mm.

6.2 Specimen size

Determine the sample size according to the test item:

Hardness test (GB/T 3849-2008): surface area>5×5 mm, thickness>2 mm.

Bending strength test (GB/T 3850-2008): 20×6.5×5.25 mm (±0.05 mm).

Fracture toughness test (GB/T 7997-2010): 20×4×2 mm (±0.02 mm).

Microstructure inspection (GB/T 3488-2008): 10×10× 5 mm (±0.1 mm).

Dimensional deviations should comply with the requirements of relevant testing standards.

6.3 Mosaic (optional)

6.3.1 Scope of application

Specimens with small size (<5×5×2 mm) or irregular shape need to be mounted.

6.3.2 Mounting steps

Use a hot mounter and choose phenolic resin or epoxy resin.

The mounting temperature is 150-180°C, the pressure is 20-30 MPa, and the holding time is 5-10 min.

After cooling, the sample is tightly bonded to the mounting material without bubbles or cracks.

6.4 Grinding and polishing

6.4.1 Coarse grinding

Use 400#-1200# sandpaper to gradually remove the cutting marks.

The speed is 200 r/min, the grinding time of each level of sandpaper is 1-2 min, and the direction is rotated 90° to ensure uniform grinding marks.

After rough grinding, the surface is smooth without obvious scratches (microscope inspection, magnification 50×).

6.4.2 Fine grinding

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Use 1500#-2000# sandpaper, speed 200 r/min, grinding time 1-2 min.

The surface roughness after fine grinding is $Ra < 0.2 \mu m$ (measured by surface roughness meter).

6.4.3 Polishing

Use diamond polishing liquid (particle size $0.5-1 \mu m$), polishing disk speed 300-400 r/min, polishing time 3-5 min.

After polishing, the surface roughness $Ra < 0.05 \mu m$, mirror-like, and scratch-free (microscope inspection, magnification 100 $\times$).

6.5 Cleaning

The sample was placed in an ultrasonic cleaner and cleaned with anhydrous ethanol for 3-5 min at a frequency of 40 kHz and a power of 100 W.

After cleaning, blow dry with dry nitrogen to ensure that there is no residue on the surface.

6.6 Sample marking

Mark the batch number, brand number (such as YG8, YT15) and test items on the non-test area of the specimen.

Marking method: Laser engraving or ink marking, the marking should be clear and should not affect the test area.

6.7 Sample inspection

Check the surface of the specimen: no cracks, scratches, oxide layers or contamination.

Check the size: Use a vernier caliper or micrometer to measure, and the deviation meets the test standard requirements.

Check surface roughness: $Ra < 0.05 \mu m$ (microstructure inspection) or $Ra < 0.1 \mu m$ (hardness test).

7. Sample preparation quality assessment

7.1 Surface quality

The surface of the specimen should be mirror-like, without scratches, cracks or processing defects (microscope inspection, magnification 100 $\times$).

Surface roughness:

Microstructure inspection: $Ra < 0.05 \mu m$.

Hardness test: $Ra < 0.1 \mu m$.

Bending strength or fracture toughness test: $Ra < 0.2 \mu m$.

7.2 Dimensional accuracy

The sample size deviation shall comply with the corresponding test standards:

Bending strength test: $\pm 0.05 mm$.

Fracture toughness test: $\pm 0.02 mm$.

Microstructure inspection: $\pm 0.1 mm$.

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7.3 Organizational Impact

No structural changes (such as coarsening of grains or cracks due to overheating) should be introduced during the specimen preparation process.

Cutting temperatures $> 60^{\circ}\text{C}$ may result in WC grain size deviations $> \pm 0.2\ \mu\text{m}$ (microscope inspection, magnification 1000 $\times$).

7.4 Non-conforming treatment

If the surface quality, size or roughness of the sample is unsatisfactory, the sample must be re-prepared.

If cracks or structural changes are found, the cause needs to be analyzed (such as cutting speed is too fast) and re-sampled.

8 Sample storage

The sample should be tested immediately after preparation to avoid prolonged exposure to air ($>24\ \text{h}$).

If storage is required, the sample should be placed in a desiccator at $20\pm 5^{\circ}\text{C}$ and humidity $<30\%$, and wrapped with anti-rust paper.

The storage time should not exceed 1 month to avoid oxidation or contamination.

9 Inspection Report

The inspection report should include the following:

Sample information: brand, batch number, size.

Preparation conditions: cutting speed (300-500 r/min), mounting temperature ($150\text{-}180^{\circ}\text{C}$), polishing liquid particle size ($0.5\text{-}1\ \mu\text{m}$).

Preparation results: surface roughness (Ra), dimensional deviation, surface quality assessment.

Evaluation conclusion: whether it meets the test requirements.

Preparation date and operator's signature.

Appendix A (Informative Appendix) Requirements for preparation of typical cemented carbide specimens

Test items	Sample size (mm)	Surface roughness (Ra, μm)	Dimensional deviation (mm)	Typical Applications
Hardness test	$>5\times 5\times 2$	<0.1	± 0.1	Cutting Tools
Bending strength test	$20\times 6.5\times 5.25$	<0.2	± 0.05	Mining drill bits
Fracture toughness test	$20\times 4\times 2$	<0.2	± 0.02	Mould
Microstructure inspection	$10\times 10\times 5$	<0.05	± 0.1	Quality Control

Appendix B (Informative Appendix) Environmental Requirements for Sample Preparation

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Temperature: 20±5°C.
Humidity: 50±10%.
No vibration, no corrosive gas environment.
Workbench levelness: deviation <0.02 mm/m.

Appendix C (Informative Appendix) Common Problems and Solutions for Sample Preparation

question	reason	Workaround
Surface scratches	Polishing liquid particle size is too large (>1 μm)	Use polishing liquid with particle size of 0.5 μm
Specimen overheated (>60°C)	Cutting speed is too fast (>500 r/min)	Reduce cutting speed to 300 r/min
Surface roughness does not meet the standard	Insufficient polishing time (<3 min)	Extend polishing time to 5 min
Specimen edge cracking	Cutting without coolant	Use water-based coolant at temperatures < 60°C

Summarize

GB/T 5249-2008 "General Specification for Preparation of Cemented Carbide Samples" provides a standardized procedure for the preparation of samples for cemented carbide performance testing. Through standardized sampling, cutting, mounting, grinding, polishing, cleaning and other steps, it ensures that the surface quality and dimensional accuracy of the samples meet the test requirements. The implementation of this standard helps to improve the accuracy and repeatability of cemented carbide performance test results, and provides reliable technical support for cutting tools, mining drills, molds and other application fields.

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appendix:

ISO 28079:2009

Fracture toughness test of cemented carbide palm-shaped specimen
Hardmetals — Palmqvist toughness test

1 Scope

This standard specifies the method for measuring the palm-shaped fracture toughness of cemented carbide and cermet by indentation at room temperature. This standard applies to the fracture toughness test of carbides and carbonitrides bonded to metals (commonly known as cemented carbides, cermets or cemented carbides), called Palmqvist fracture toughness, which is calculated by measuring the total length of the four-corner crack of the Vickers hardness indentation. The test procedure of this standard is applicable to ambient temperature ($20\pm 5^{\circ}\text{C}$), but can be extended to higher or lower temperatures by agreement. This standard test procedure is applicable to conventional laboratory air environment and is not applicable to corrosive environments (such as strong acids or sea water).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

ISO 3878:1983 Cemented carbide — Vickers hardness and Rockwell hardness test

ISO 3252:1999 Powder metallurgy — Terminology

ISO 6507-1:2005 Metallic materials — Vickers hardness test Part 1: Test method

3 Terms and definitions

This standard adopts ISO 3252:1999 and the following terms and definitions:

Hardmetals

A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy.

Cermets

with carbonitride (such as TiCN) as the main hard phase and metal (such as Ni, Co) as the bonding phase.

Palmqvist Toughness

The fracture toughness of cemented carbide or cermet is calculated by the total length of the four-corner crack of the Vickers hardness indentation, and the unit is $\text{MPa}\cdot\text{m}^{1/2}$.

Vickers hardness indentation

A Vickers diamond indenter (vertex angle 136°) is used to apply load, forming a square indentation on the surface of the specimen.

Crack length (l)

The length of the palm-shaped crack extending from the four corners of the Vickers indentation, in mm.

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4 Test Principle

The palm-shaped fracture toughness test applies a Vickers hardness indentation on the surface of a cemented carbide or cermet specimen, measures the total length of the palm-shaped crack extending from the four corners of the indentation, and calculates the fracture toughness K_{Ic} by combining the indentation load and the material hardness. The palm-shaped crack is assumed to be a superficial crack (non-median crack), and its length is related to the material toughness. The calculation formula is as follows:

$$K_{Ic} = A \times \sqrt{HV} \times \sqrt{\frac{P}{T}}$$

其中:

- K_{Ic} 为断裂韧性, 单位为 $\text{MPa} \cdot \text{m}^{1/2}$;
- A 为常数 (经验值, 通常取 0.0028) ;
- HV 为维氏硬度, 单位为 N/mm^2 (或 MPa) ;
- P 为压痕载荷, 单位为 N (通常为 294.2 N , 即 30 kgf) ;
- T 为四角裂纹总长度, 单位为 mm , $T = l_1 + l_2 + l_3 + l_4$.

5 Test equipment

5.1 Vickers hardness tester

Meets ISO 6507-1:2005 requirements.

Load range: 100-500 N , accuracy $\pm 0.5\%$.

Holding time control: 5-60 s , deviation $< \pm 0.5$ s.

5.2 Indenter

Standard Vickers diamond indenter, vertex angle $136^\circ (\pm 0.5^\circ)$.

The surface of the indenter is free of defects and has clear edges (microscope inspection, resolution $< 0.5 \mu\text{m}$).

5.3 Measurement device

Optical microscope: magnification $400\times$ - $600\times$, resolution $< 0.5 \mu\text{m}$.

Equipped with a digital readout system with a measurement accuracy of $\pm 0.001 \text{ mm}$.

5.4 Calibration Block

Carbide standard calibration blocks, hardness range HV 1200-2000, deviation $\leq \pm 2\%$.

The surface roughness of the calibration block is $R_a < 0.05 \mu\text{m}$.

5.5 Environmental Control

Temperature: $20 \pm 5^\circ\text{C}$.

Humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

6. Sample preparation

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6.1 Sample requirements

Specimen shape: cuboid or cylinder, test surface area $>5 \times 5$ mm, thickness >2 mm.

The test surface should be flat and free of cracks, oxide layers or machining defects.

Surface roughness $R_a < 0.1 \mu\text{m}$ (polished).

6.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure statistical representativeness.

If the result deviation is large ($>5\%$), the number of samples needs to be increased to 10.

6.3 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

7 Test steps

7.1 Equipment Calibration

The hardness tester was calibrated using a standard calibration block with a load of 294.2 N (30 kgf) and three measurements. The hardness deviation was $< \pm 1\%$.

Check the condition of the indenter to ensure there is no wear or defects.

7.2 Test conditions

Ambient temperature: $20 \pm 5^\circ\text{C}$.

Relative humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

7.3 Vickers hardness indentation

Place the specimen on the hardness tester workbench, making sure the test surface is level.

Select a load of 294.2 N (30 kgf) and a holding time of 10-15 s.

The indenter is slowly pressed into the sample surface and automatically unloaded after maintaining the load.

5 indentations were made on each specimen, with the indentation spacing > 5 times the indentation diagonal length (> 0.5 mm) and the distance from the specimen edge > 1 mm.

7.4 Crack length measurement

An optical microscope (magnification $400\times$ - $600\times$) was used to measure the crack lengths l_1 , l_2 , l_3 , and l_4 at the four corners of the indentation with an accuracy of ± 0.001 mm.

Calculate the total crack length:

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$$T = l_1 + l_2 + l_3 + l_4$$

Confirm that the crack is a palm-shaped crack (not a median crack or a lateral crack), and the crack should extend clearly from the four corners of the indentation.

7.5 Vickers hardness measurement

Measure the lengths of the two diagonals of the indentation (d_1 , d_2) with an accuracy of ± 0.001 mm.

Compute the average diagonal length:

$$d = \frac{d_1 + d_2}{2}$$

Calculate Vickers hardness:

$$HV = \frac{1.8544 \times P}{d^2}$$

Where: $P = 294.2$ N.

7.6 Fracture toughness calculation

Calculate the fracture toughness using the formula:

$$K_{Ic} = 0.0028 \times \sqrt{HV} \times \sqrt{\frac{P}{T}}$$

Take the average value of K_{Ic} of 5 indentations, with a deviation of $< \pm 5\%$.

8 Evaluation of test results

8.1 Fracture toughness range

The palm fracture toughness value of cemented carbide is usually $K_{Ic} \in 10-20 \text{ MPa} \cdot \text{m}^{1/2}$, and the specific range depends on the grade and Co content:

YG6 (6% Co): $K_{Ic} \in 14-16 \text{ MPa} \cdot \text{m}^{1/2}$.

YG8 (8% Co): $K_{Ic} \in 12-15 \text{ MPa} \cdot \text{m}^{1/2}$.

YG10 (10% Co): $K_{Ic} \in 10-13 \text{ MPa} \cdot \text{m}^{1/2}$.

Metal ceramics (such as TiCN -Ni): $K_{Ic} \in 8-12 \text{ MPa} \cdot \text{m}^{1/2}$.

8.2 Deviation Assessment

The K_{Ic} value deviation of the 5 indentations is $< \pm 5\%$, otherwise retesting is required.

If the K_{Ic} value is outside the expected range, the cause needs to be analyzed (e.g., the crack morphology is not palm-shaped, or the Co content is too high resulting in no cracks).

8.3 Analysis of influencing factors

Crack shape: If the crack is a median crack or a lateral crack (not a palm-shaped crack), the K_{Ic} value is invalid.

Co content: When the Co content is $> 15\%$, no cracks may be generated (toughness is too high) and

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the palm method is not applicable.

Load selection: A load that is too low (<294.2 N) may not generate cracks, while a load that is too high (>490.3 N) may cause crack complication.

Surface quality: Surface roughness $R_a > 0.1 \mu\text{m}$ will affect the crack length measurement (deviation >5%).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size, Co content.

Test conditions: equipment model, load (294.2 N), holding time (10-15 s), ambient temperature ($20 \pm 5^\circ\text{C}$), humidity ($50 \pm 10\%$).

T for each indentation T, Vickers hardness HV HV HV, K_{Ic} values and their average values and deviations.

Evaluation conclusion: whether it meets the expected range, description of crack morphology.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference values of palm-shaped fracture toughness of typical cemented carbides

Brand	Co content (wt %)	Vickers hardness (HV30)	Palm fracture toughness (K_{Ic} , $\text{MPa} \cdot \text{m}^{1/2}$)	Typical Applications
YG6	6	1500-1600	14-16	Mining drill bits
YG8	8	1450-1550	12-15	Cutting Tools
YG10	10	1400-1500	10-13	Mould
TiCN Ni	10	1600-1700	8-12	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: $20 \pm 5^\circ\text{C}$.

Humidity: $50 \pm 10\%$.

No vibration, no corrosive gas environment.

Test bench levelness: deviation $< 0.02 \text{ mm/m}$.

Appendix C (Informative Appendix) Schematic diagram of palm-shaped crack morphology

Palm-shaped crack: A shallow crack extending from the four corners of the Vickers indentation, with the crack path clearly visible along the edge of the indentation.

Non-palm-shaped cracks:

Median Crack: The crack extends vertically downward from the bottom of the indentation.

Lateral Crack: A crack that propagates laterally along the specimen surface and may cause spalling.

Note: Only palm-shaped cracks are applicable to the calculation of K_{Ic} in this standard.

Summarize

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ISO 28079:2009 "Test for fracture toughness of palm-shaped specimens of cemented carbide" provides a standardized procedure for palm-shaped fracture toughness testing of cemented carbide and cermets, ensuring the accuracy and repeatability of test results through standardized specimen preparation, indentation testing, crack measurement and result calculation. The implementation of this standard helps the quality control and performance evaluation of cemented carbide, and provides reliable technical support for cutting tools, mining drills, molds and other application fields.

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appendix:

ISO 6507-1:2018

Vickers hardness test of metal materials Metallic materials — Vickers hardness test

1 Scope

This standard specifies the method for determining the hardness of metal materials (including cemented carbide, steel, cast iron, non-ferrous metals, etc.) at room temperature (10°C to 35°C) through the Vickers hardness test, including test principles, equipment requirements, sample preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to tests in the Vickers hardness range of HV 1 to HV 3000, covering different loads (0.098 N to 2942 N). This standard is not applicable to hardness tests of tiny or thin-walled specimens (thickness <0.1 mm) or coated materials.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard. ISO 6507-2:2018 Metallic materials — Vickers hardness test Part 2: Verification and calibration of hardness testers

ISO 6507-3:2018 Metallic materials — Vickers hardness test Part 3: Calibration standards

ISO 376:2011 Metallic materials — Calibration force standards

ISO 18265:2013 Metallic materials — Conversion between hardness and strength

3 Terms and definitions

This standard uses the following terms and definitions:

Vickers Hardness (HV): The ability of a metal material to resist the penetration of a Vickers indenter, expressed as a Vickers hardness value in N/mm² (or MPa), calculated by the diagonal length of the indentation.

Vickers indenter: A square diamond pyramid indenter with a vertex angle of 136°.

Indentation diagonal: The length of the two diagonals of the square indentation formed when the Vickers indenter is pressed into the sample surface, in mm.

Test load (F): The force applied to the Vickers indenter in Newtons (N), ranging from 0.098 N to 2942 N.

Holding time : The time the indenter maintains the load after applying it, measured in seconds (s).

4 Test Principle

The Vickers hardness test is carried out by pressing a standard Vickers diamond indenter (vertex angle 136°) into the surface of a metal sample with a specified load, holding it for a certain period of time and then unloading it, measuring the length of the two diagonals of the indentation (d1, d2), calculating the average diagonal length (d), and then calculating the Vickers hardness value (HV).

The calculation formula is:

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$$HV = \frac{1.8544 \times F}{d^2}$$

in:

F 为试验载荷, 单位为 N;

d 为压痕两条对角线的平均长度, 单位为 mm, $d = \frac{d_1 + d_2}{2}$;

硬度值单位为 N/mm² (1 kgf/mm² $\approx$ 9.807 N/mm²) 。

5 Test equipment

5.1 Vickers hardness tester

Meets ISO 6507-2:2018 verification and calibration requirements.

Load range: 0.098 N to 2942 N (HV 0.01 to HV 30), accuracy $\pm 0.5\%$.

Holding time control: 5 s to 60 s, deviation $\leq \pm 0.5$ s.

5.2 Indenter

Standard Vickers diamond indenter, vertex angle 136° ($\pm 0.5^\circ$).

The surface of the indenter is free of defects and has clear edges (microscope inspection, resolution $< 0.5 \mu\text{m}$).

5.3 Measurement device

Optical microscope: magnification 50×-1000×, 400× recommended, resolution $< 0.5 \mu\text{m}$.

Equipped with a digital readout system with a measurement accuracy of ± 0.001 mm.

5.4 Calibration Block

Standard calibration blocks in accordance with ISO 6507-3:2018, hardness range HV 100-3000, deviation $\leq \pm 2\%$.

The surface roughness of the calibration block is $R_a < 0.05 \mu\text{m}$.

5.5 Environmental Control

Temperature: 10°C to 35°C, 20 $\pm$ 5°C recommended.

Humidity: 30%-80%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, cylinder or other regular geometric shape, test surface area $> 5 \times 5$ mm, thickness > 0.5 mm (load dependent).

The test surface should be flat and free of cracks, oxide layers or machining defects.

Surface roughness $R_a < 0.1 \mu\text{m}$ (polished), for low load (< 9.807 N) testing, $R_a < 0.05 \mu\text{m}$.

The thickness of the specimen should meet the following requirements: thickness $\geq 1.5 \times$ diagonal length of the indentation.

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6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness. If the result deviation is large ($>3\%$), the number of samples needs to be increased to 5.

6.3 Sample marking

The specimens should be marked with batch number, brand (such as YG8, 45# steel) and test items, and the marking should not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol or acetone to remove oil, dust, and use it after drying.

7 Test steps

7.1 Equipment Calibration

Use the standard calibration block to calibrate the hardness tester. Select the calibration block that matches the test load. Measure 3 times. The hardness deviation is $\leq \pm 1\%$. Check the condition of the indenter to ensure there is no wear or defects.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 5^{\circ}\text{C}$ recommended.

Relative humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Load selection

Select the load based on the material hardness and specimen thickness:

Carbide: 294.2 N (30 kgf, HV 30) is recommended.

Steel: 50 N to 294.2 N (HV 5 to HV 30).

Thin-walled specimens: 0.098 N to 9.807 N (HV 0.01 to HV 1).

The load should ensure that the diagonal length d of the indentation is in the range 0.020 mm to 1.400 mm.

7.4 Test operation

Place the specimen on the hardness tester workbench, making sure the test surface is level.

Select an appropriate load (e.g. 294.2 N) and hold the load for 10-15 s (or adjust according to material requirements).

The indenter is slowly pressed into the sample surface and automatically unloaded after maintaining the load.

5 indentation points shall be measured for each specimen, with the indentation spacing > 3 times the diagonal length (> 0.3 mm) and the distance from the specimen edge to > 0.5 mm.

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7.5 Measurement and calculation

The lengths of the two diagonal lines of the indentation (d_1 , d_2) were measured using an optical microscope with an accuracy of ± 0.001 mm.

Calculate the average diagonal length:

$$d = \frac{d_1 + d_2}{2}$$

Calculate Vickers hardness:

$$HV = \frac{1.8544 \times F}{d^2}$$

five indentation points is taken as the hardness value of the sample, with a deviation of $< \pm 3\%$.

8 Evaluation of test results

8.1 Hardness value range

Vickers hardness range of metal materials: HV 100-3000, the specific value depends on the material :

Cemented Carbide (YG8): HV 1450-1550.

Hardened steel (45#): HV 500-700.

Aluminium alloy: HV 50-150.

8.2 Deviation Assessment

the 5 indentation points is $< \pm 3\%$, otherwise retesting is required.

If the hardness value exceeds the material technical requirements, the cause needs to be analyzed (such as surface defects, load mismatch).

8.3 Analysis of influencing factors

Load selection: If the load is too low (< 0.098 N), a clear indentation may not be formed; if the load is too high (> 2942 N), the specimen may be deformed.

Surface quality: Surface roughness $R_a > 0.1$ μm will result in lower hardness values (deviation $> 5\%$).

Dwell time : A time < 5 s or > 60 s will affect the indentation size (deviation $\pm 2\%$).

Specimen thickness: Thickness $< 1.5 \times$ indentation diagonal length will lead to support effect and high hardness value (deviation $> 10\%$).

9 Test Report

The test report should include the following:

Sample information: material type, brand, batch number, size.

Test conditions: equipment model, load (N), holding time (s), ambient temperature (10°C to 35°C), humidity (30%-80%).

Test results: average diagonal length of each indentation (d), hardness value (HV), average hardness value and deviation.

Evaluation conclusion: whether it meets the technical requirements of the material.

Test date and operator's signature.

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Appendix A (Informative Appendix) Vickers hardness reference values for typical metal materials

Material Type	Brand/category	Vickers hardness (HV)	Typical load (N)	Typical Applications
Cemented Carbide	YG8	1450-1550	294.2	Cutting Tools
Hardened steel	45# (HRC 50)	500-700	294.2	Mechanical parts
Aluminum Alloy	6061-T6	50-150	9.807	Aerospace structures
cast iron	HT250	200-300	98.07	Engine block

Appendix B (Informative Appendix) Table of the relationship between Vickers hardness and load

Load(N)	Hardness symbol	Diagonal length range of indentation (mm)	Applicable Materials
0.098	HV 0.01	0.020-0.050	Thin wall or small specimens
9.807	HV 1	0.050-0.150	Soft metals (such as aluminum)
98.07	HV 10	0.150-0.400	Medium hard materials (such as cast iron)
294.2	HV 30	0.400-1.000	Hard alloy, steel
2942	HV 300	1.000-1.400	Superhard materials

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

ISO 6507-1:2018 "Vickers hardness test for metallic materials" provides a standardized procedure for Vickers hardness testing of metallic materials, ensuring the accuracy and repeatability of test results through standardized specimen preparation, test steps and result evaluation. The implementation of this standard is applicable to the quality control and performance evaluation of materials such as cemented carbide, steel, and aluminum alloys, providing reliable technical support for application fields such as machinery manufacturing, aerospace, and mold manufacturing.

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appendix:

ISO 6507-1:2018

Metallic Materials - Vickers Hardness Test

Part 1: Test methods

1 Scope

This standard specifies the Vickers hardness test method for metal materials (including cemented carbide), applicable to the test with a test force range of 1.961 N (0.2 kgf) to 1,177 N (120 kgf). It includes macro Vickers hardness test (test force 9.807 N to 1,177 N) and micro Vickers hardness test (test force 1.961 N to 9.807 N). This standard is applicable to the hardness test of various metal materials, including steel, cast iron, non-ferrous metals and cemented carbide, and provides test procedures, measurement methods and result processing requirements.

2 Normative references

The clauses listed in the following documents become the clauses of this standard through reference in this standard. For referenced documents with dates, only the referenced versions apply; for referenced documents without dates, the latest versions (including all amendments) apply.

ISO 6507-2:2018 Metallic materials — Vickers hardness test Part 2: Verification and calibration of hardness testers

ISO 6507-3:2018 Metallic materials — Vickers hardness test Part 3: Calibration of reference blocks

ISO 376:2011 Metallic materials — Calibration of force measuring systems for static tension, compression and thrust testing machines

3 Terms and definitions

This document applies to ISO 3850:2018 (Terminology for cemented carbides) and the following definitions:

Vickers hardness (HV) : The hardness value determined by the ratio of the applied test force to the indentation surface area, with units of HV.

Test force (F) : The force applied by the indenter to the specimen, expressed in Newtons (N) or kilograms-force (kgf).

Indentation : A square indentation formed on the surface of the sample by a diamond quadrangular pyramid indenter.

Diagonal length (d) : The average length of the two diagonals of the indentation, in millimeters (mm).

4 Principle

The determination of Vickers hardness is based on applying a specific test force, pressing a diamond quadrangular pyramid indenter (vertex angle 136°) into the sample surface, measuring the diagonal length of the indentation, and calculating the hardness value. The hardness value is calculated according to the following formula: $HV=1.8544 \cdot F / d^2$

in:

HV is Vickers hardness (unit: kgf /mm² or N/ mm²),

F is the applied test force (unit: N),

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d is the average diagonal length of the indentation (unit: mm).

5 Test equipment

5.1 Vickers hardness tester

Test force range: 1.961 N to 1,177 N, accuracy $\pm 1.0\%$.

Indenter: Diamond quadrangular pyramid, apex angle $136^{\circ} \pm 0.5^{\circ}$, tip radius < 0.002 mm.

Measuring system: Microscope with magnification $200\times$ to $500\times$, resolution ≤ 0.001 mm.

Loading time: 10 to 15 seconds, accuracy ± 1 second.

5.2 Environmental Control

Temperature: 10°C to 35°C , $23 \pm 2^{\circ}\text{C}$ recommended.

Humidity: 30% to 70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample requirements

6.1 Shape and size

The specimen should be large enough to ensure that the indentation is at least 2.5 times the diagonal length from the edge and adjacent indentations.

Recommended thickness: at least 0.5 times the maximum indentation depth corresponding to the test force (approximately $0.07 \times d$).

6.2 Surface preparation

The surface roughness $R_a \leq 0.2 \mu\text{m}$, must be flat, without oxide layer or cracks.

Use 600# to 2500# diamond sandpaper for grinding and $0.25 \mu\text{m}$ aluminum oxide polishing liquid for polishing.

6.3 Number of samples

Each batch shall have at least 3 specimens, which may be increased to 5 in special cases to ensure representativeness.

7 Test procedures

7.1 Equipment Calibration

Verification of hardness testers according to ISO 6507-2, including calibration of test force, indenter and measuring system.

7.2 Test conditions

Select the test force appropriate for the material (see Table 1).

Make sure the specimen surface is clean and free of dust or oil before loading.

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7.3 Test operation

Place the sample on the hardness tester workbench and adjust it to be level.

Select a test force and apply the load for 10 to 15 seconds.

After the load is removed, the lengths of the two diagonals of the indentation, d_1 and d_2 , are measured using a microscope.

Calculate the average diagonal length $d = (d_1 + d_2) / 2$.

Measure at least 3 different locations on the specimen with an interval of ≥ 2.5 mm.

7.4 Calculation of results

Calculate Vickers hardness:

$$HV = \frac{1.8544 \cdot F}{d^2}$$

Calculate the average:

$$\bar{HV} = \frac{\sum HV_i}{n}$$

Where HV_i is a single measurement value and n is the number of measurements.

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (HV_i - \bar{HV})^2}{n - 1}}$$

Ensure that the measured value deviation is $< \pm 2.0\%$.

8 Test force selection

Material Type Recommended test force (N) Typical hardness range (HV)

Cemented Carbide 9.807 - 98.07 1000 - 2000

Hardened steel 9.807 - 294.2 500 - 1000

Non-ferrous metals 1.961 - 9.807 50 - 200

Note: The test force should be selected according to the material hardness and specimen thickness.

9 Results Evaluation

9.1 Hardness range

The hardness value should be consistent with the material properties, for example, the hardness range of YG6 cemented carbide is 1400-1600 HV.

9.2 Deviation Assessment

the three measuring points is $< \pm 2.0\%$, and the standard deviation is < 20 HV, otherwise retesting is required.

9.3 Influencing factors

Surface roughness : $R_a > 0.2$ μm may result in a 5%-10% lower hardness value.

Test force : A force deviation of $\pm 1.0\%$ may result in a 2%-3% deviation in the result.

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Loading time : Times <10 s or >15 s may affect the indentation shape.

10 Test Report

The test report should include the following:

Sample information: material type, brand, size.

Test conditions: hardness tester model, test force, loading time, ambient temperature (10°C to 35°C), humidity (30%-70%).

Test results: hardness value at each point, average value, standard deviation and deviation.

Evaluation conclusion: whether it meets the technical requirements.

Test date and operator signature.

Appendix A (Informative Appendix) Reference values of hardness of typical metal materials

Material Type	Brand/State	Hardness range (HV)	Typical Applications
Cemented Carbide	YG6	1400-1600	Mining drill bits
Hardened steel	42CrMo	500-700	Mechanical Components
Non-ferrous metals	Cu-ETP	50-100	Electrical materials

Appendix B (Informative Appendix) Environmental Requirements

Temperature: 10°C to 35°C, 23±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

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appendix:

ISO 6507-2:2018

Metallic Materials - Vickers Hardness Test

Part 2: Verification and calibration of hardness testers

1 Scope

This standard specifies methods for verification and calibration of Vickers hardness testing machines for determining the Vickers hardness of metallic materials (including cemented carbides) in accordance with ISO 6507-1. It covers direct and indirect verification methods to ensure the accuracy and reliability of hardness measurements. This standard applies to macro and micro Vickers hardness testing machines with a test force range of 1.961 N (0.2 kgf) to 1,177 N (120 kgf), including periodic inspection and maintenance procedures.

2 Normative references

The clauses listed in the following documents become the clauses of this standard through reference in this standard. For referenced documents with dates, only the referenced versions apply; for referenced documents without dates, the latest versions (including all amendments) apply.

ISO 6507-1:2018 Metallic materials — Vickers hardness test Part 1: Test method

ISO 6507-3:2018 Metallic materials — Vickers hardness test Part 3: Calibration of reference blocks

General requirements for the competence of testing and calibration laboratories

3 Terms and definitions

This document applies the terms and definitions given in ISO 6507-1:2018 and includes the following definitions:

Direct Verification : The process of verifying the performance of a Vickers hardness tester by directly measuring its components, such as test force, indenter geometry and measurement system.

Indirect Verification : The process of verifying the performance of a Vickers hardness testing machine by testing a standardized reference block.

Vickers hardness (HV) : The hardness value determined by the ratio of the applied test force to the indentation surface area, with units of HV.

Test Force : The force applied by the indenter to the specimen, expressed in Newtons (N) or kilograms-force (kgf).

4 General requirements

4.1 Scope

This standard applies to all Vickers hardness testing machines, covering the test force range from 1.961 N to 1,177 N, including manual, semi-automatic, and fully automatic machines.

4.2 Responsibility

Verification and calibration shall be performed by qualified personnel or trained operators in accordance with the requirements of ISO/IEC 17025.

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4.3 Frequency

Initial verification : performed after the hardness tester is delivered or repaired.

Periodic verification : At least once every 12 months , or after significant use (e.g. 10,000 tests).

Intermediate inspection : Perform a simple inspection before each use to ensure that basic functions are normal.

5 Direct Verification

5.1 Test force verification

Equipment : Use a calibrated force sensor with an accuracy of $\pm 0.5\%$.

program :

Apply a test force (1,961 N to 1,177 N) and record the actual force value.

Ensure that the force value deviation is within $\pm 1.0\%$.

Record : Record the force value and deviation of each measurement.

5.2 Verification of indenter geometry

Equipment : Use an optical microscope or standard indentation comparison method with a magnification of $\geq 200\times$.

program :

Check the diamond indenter top angle ($136^\circ \pm 0.5^\circ$) and tip radius (< 0.002 mm).

Make sure the indenter is not cracked or worn.

Record : Record the pressure head parameters and inspection results.

5.3 Measurement system verification

Equipment : Use a calibrated microscope with a resolution of ≤ 0.001 mm.

program :

Measure the diagonal length of the standard indentation, with a deviation of $\leq \pm 0.5\%$.

Verify the consistency of the measurement system across the entire magnification range.

Record : Record diagonal length measurements and deviations.

6 Indirect Verification

6.1 Reference Block Requirements

Using reference blocks calibrated in accordance with ISO 6507-3, the hardness range covers typical values within the test force range .

The surface roughness of the reference block is $R_a \leq 0.2 \mu\text{m}$.

6.2 Test Procedure

Preparation : Select at least 5 reference blocks of different hardness values.

operate :

At least 5 measurements were performed on each reference block, with an interval of ≥ 2.5 mm.

Record the hardness value for each measurement.

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calculate :

Calculate the mean hardness value and standard deviation.

Ensure that the measured value is within $\pm 2.0\%$ of the reference block calibration value .

6.3 Result evaluation

If the deviation exceeds $\pm 2.0\%$, the hardness tester needs to be adjusted or repaired and re-verified.

7 Calibration

7.1 Calibration cycle

Calibration should be performed after each direct verification or after an indirect verification failure.

It is recommended to calibrate once a year, or adjust according to the frequency of use.

7.2 Calibration Procedure

Test force calibration : Use standard weights to adjust the force value, the deviation is $< \pm 0.5\%$.

Indenter calibration : Replace or grind the indenter to ensure the geometry meets the requirements.

Measuring system calibration : Use a standard scale to adjust the microscope, with a deviation of $< \pm 0.2\%$.

7.3 Calibration certificate

Provide calibration certificate including equipment number, calibration date, operator signature and uncertainty analysis.

8 Maintenance and Records

8.1 Maintenance

Clean the pressure head and measuring system regularly to avoid dust or oil.

Check electrical connections and mechanical parts to ensure nothing is loose.

8.2 Records

Keep records of each verification and calibration for at least 5 years, including raw data and analysis of results.

9 Test Report

The test report should include the following:

Durometer model and serial number.

Test date and environmental conditions (temperature 10°C to 35°C , humidity 30%-70%).

Direct verification of results (test force, indenter, measurement system data).

Indirect verification results (reference block number, measurement value, deviation).

Calibration results (data before and after adjustment, uncertainty).

Signature of the person verifying and calibrating.

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Appendix A (Informative Appendix) Typical Verification Parameter Reference Values

Test force(N)	Force deviation(%)	Indenter top angle deviation (°)	Measurement system deviation (%)
9.807	±1.0	±0.5	±0.5
98.07	±1.0	±0.5	±0.5
1177	±1.0	±0.5	±0.5

Appendix B (Informative Appendix) Environmental Requirements

Temperature: 10°C to 35°C, 23±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Summarize

ISO 6507-2:2018 "Metallic materials - Vickers hardness test Part 2: Verification and calibration of hardness testers" provides an international standardized procedure for the verification and calibration of Vickers hardness testing machines, ensuring the accuracy and reliability of measurement results through direct and indirect methods. The implementation of this standard helps to improve the quality control of hardness testing and provide technical support for the performance evaluation of metallic materials (including cemented carbide).

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appendix:

ISO 6507-3:2018

Metallic Materials - Vickers Hardness Test

Part 3: Calibration Standards

1 Scope

This standard specifies the calibration method of standard blocks for Vickers hardness test to ensure the accuracy and traceability of hardness values. It is applicable to Vickers hardness test of metal materials (including cemented carbide). The hardness range of standard blocks covers 20 HV to 2000 HV, and the test force range is 1.961 N (0.2 kgf) to 1,177 N (120 kgf), including macro Vickers hardness (test force 9.807 N to 1,177 N) and micro Vickers hardness (test force 1.961 N to 9.807 N). This standard is applicable to calibration laboratories and hardness tester users to verify the performance of Vickers hardness testing machines.

2 Normative references

The clauses listed in the following documents become the clauses of this standard through reference in this standard. For referenced documents with dates, only the referenced versions apply; for referenced documents without dates, the latest versions (including all amendments) apply.

ISO 6507-1:2018 Metallic materials — Vickers hardness test Part 1: Test method

ISO 6507-2:2018 Metallic materials — Vickers hardness test Part 2: Verification and calibration of hardness testers

General requirements for the competence of testing and calibration laboratories

3 Terms and definitions

This document applies the terms and definitions given in ISO 6507-1:2018 and includes the following definitions:

Standard Block : A metal block with a known hardness value and uniform microstructure used to calibrate a Vickers hardness testing machine.

Calibration : The process of determining the hardness value and its uncertainty of a standard block by comparison with a higher grade standard.

Traceability : Property of relating measurement results to international or national standards through an unbroken chain of comparisons.

Vickers hardness (HV) : The hardness value determined by the ratio of the applied test force to the indentation surface area, with units of HV.

4 Standard Block Requirements

4.1 Material requirements

The standard block material should have a uniform microstructure with a hardness deviation of $<\pm 1.0\%$.

Common materials: Hardened steel, cemented carbide or copper alloys in the hardness range from 20 HV to 2000 HV.

Surface roughness $R_a \leq 0.1 \mu\text{m}$, no cracks, oxide layer or inclusions.

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4.2 Size requirements

Recommended size: diameter 50 mm or 50×50 mm, thickness ≥ 6 mm (macro-Vickers) or ≥ 1 mm (micro-Vickers).

The flatness deviation of the test surface is <0.005 mm.

4.3 Hardness uniformity

The hardness deviation of the standard block test surface is $<\pm 1.0\%$, verified by measuring at least 5 points .

5. Calibration equipment

5.1 Vickers hardness tester

Meets ISO 6507-2 requirements, test force accuracy $\pm 0.5\%$, indenter top angle $136^\circ \pm 0.5^\circ$.

The measurement system resolution is ≤ 0.001 mm and the deviation is $<\pm 0.5\%$.

5.2 Environmental Control

Temperature: $20^\circ\text{C} \pm 1^\circ\text{C}$.

Humidity: 30% to 70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

5.3 Reference equipment for calibration

Using nationally or internationally recognized higher grade standard blocks, the hardness uncertainty is $<\pm 0.5\%$.

6 Calibration Procedure

6.1 Preparation

Clean the surface of the standard block to ensure there is no dust or oil.

Calibrate Vickers hardness testers in accordance with ISO 6507-2.

6.2 Test conditions

Select the test force: according to the hardness range of the standard block (see Table 1).

Loading time: 10 to 15 seconds, accuracy ± 1 second.

6.3 Calibration Operation

Measure at least 5 evenly distributed positions on the test surface of the standard block, with an interval of ≥ 2.5 mm .

d_1 and d_2 of each indentation were measured , and the average value $d = (d_1 + d_2) / 2$ was calculated.

Calculate Vickers hardness: $HV = 1.8544 \cdot F / d^2$

Where F is the test force (N) and d is the average diagonal length (mm).

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6.4 Result processing

Calculate the average hardness value of 5 measurement points:

$$\bar{HV} = \frac{\sum HV_i}{5}$$

Calculate the standard deviation:

$$s = \sqrt{\frac{\sum (HV_i - \bar{HV})^2}{4}}$$

Ensure hardness deviation $< \pm 1.0\%$ and standard deviation < 5 HV.

7 Test force selection

Hardness range (HV)	Recommended test force (N)	Application Type
20 - 200	1.961 - 9.807	Microscopic Vickers
200 - 1000	9.807 - 98.07	Macro Vickers
1000 - 2000	98.07 - 294.2	Carbide Testing

8 Uncertainty assessment

8.1 Sources of uncertainty

Deviation of test force: $\pm 0.5\%$ may result in a deviation of hardness of $\pm 1.0\%$.

Diagonal measurement deviation: $\pm 0.5\%$ may result in a hardness deviation of $\pm 1.0\%$.

Temperature fluctuations: $\pm 1^\circ\text{C}$ may result in a hardness deviation of $\pm 0.5\%$.

8.2 Uncertainty calculation

Comprehensive uncertainty U (expanded uncertainty, $k=2$):

$$U = 2 \cdot \sqrt{u_{\text{force}}^2 + u_{\text{diagonal}}^2 + u_{\text{temp}}^2}$$

Typical uncertainty: $\pm 2\%$ (approx. ± 20 HV for hardness values of 1000 HV).

9 Calibration certificate

The calibration certificate should contain the following:

Standard block number and material information.

Calibration date and environmental conditions (temperature $20^\circ\text{C} \pm 1^\circ\text{C}$, humidity 30%-70%).

Test force and hardness value, mean value and standard deviation of 5 measuring points.

Uncertainty analysis (expanded uncertainty, $k=2$).

Name and signature of the calibration body.

10 Maintenance and use of standard blocks

10.1 Maintenance

Store in a desiccator to avoid oxidation or contamination.

Check the surface condition regularly. When the surface roughness $R_a > 0.1 \mu\text{m}$, it needs to be re-

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polished.

10.2 Use

Clean the surface before each use to avoid dust or oil from affecting the measurement.
After being used for more than 100 times, recalibration is required.

Appendix A (Informative Appendix) Reference values of hardness of typical standard blocks

Material Type	Hardness range (HV)	Test force(N)	Typical Applications
Cemented Carbide	1400-1600	98.07	Calibration of carbide test
Hardened steel	500-700	49.03	Calibration Steel Testing
Copper Alloy	50-100	4.903	Calibration for non-ferrous metal testing

Appendix B (Informative Appendix) Environmental Requirements

Temperature: 20°C ±1°C.
Humidity: 30%-70%, 50±10% recommended.
No vibration, no corrosive gas environment.
Test bench levelness: deviation <0.02 mm/m.

appendix:

ISO 3327:2009

Test method for compressive strength of cemented carbide
Hardmetals — Determination of transverse rupture strength

1 Scope

This standard specifies the method for determining the transverse rupture strength of cemented carbide by three-point or four-point bending test at room temperature (10°C to 35°C), including test principle, equipment requirements, sample preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to cemented carbide with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and also to cemented carbide with other carbides (such as TaC, TiC, VC). This standard is not applicable to coated cemented carbide or cemented carbide after surface strengthening (such as carburized layer compressive strength test).

Note: The "compressive strength" in this standard is interpreted as transverse rupture strength (TRS) according to user request. Since the compressive strength of cemented carbide is usually much higher than its bending strength, ISO 3327:2009 mainly focuses on the transverse rupture strength test.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

ISO 3878:1983 Cemented carbide — Vickers hardness and Rockwell hardness test

ISO 4506:1979 Cemented carbide — Preparation of test specimens and test conditions

ISO 3611:2010 Cemented carbide — Terminology

ISO 7500-1:2015 Metallic materials — Force standards for tensile and compression testing Part 1: Calibration force standards

3 Terms and definitions

This standard adopts ISO 3611:2010 and the following terms and definitions:

Hardmetals: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

Transverse Rupture Strength (TRS): The maximum stress that a cemented carbide specimen withstands in a three-point or four-point bending test, measured in MPa, reflects the material's ability to resist bending fracture.

Three-point bending: A bending test in which a single-point load is applied to the specimen at two supporting points.

Four-point bending: A bending test in which a uniform load is applied to the specimen between two support points and two loading points.

4 Test Principle

The transverse rupture strength test applies a three-point or four-point bending load to the cemented carbide specimen until the specimen breaks, records the maximum rupture load, and calculates the

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transverse rupture strength (TRS) based on the specimen geometry. The calculation formula varies depending on the test type:

Three-point bending:

$$TRS = \frac{3FL}{2bh^2}$$

Four-point bending:

$$TRS = \frac{3FL}{4bh^2} \times \frac{l_1}{l}$$

in:

F is the maximum breaking load, in N;

L is the support span, in mm;

l_1 is the distance between loading points, in mm (only for four-point bending);

b is the width of the specimen, in mm;

h is the specimen thickness in mm.

5 Test equipment

5.1 Universal testing machine

Load range: 0-50 kN , accuracy $\pm 0.5\%$.

Loading speed control: 0.1-1 mm/min, deviation $< \pm 0.05$ mm/min.

Meets ISO 7500-1:2015 calibration requirements.

5.2 Fixture

Three-point bending fixture: support span 14.5 mm (± 0.05 mm), support point diameter 2 mm (± 0.02 mm).

Four-point bending fixture: support span 20 mm (± 0.05 mm), loading point spacing 10 mm (± 0.05 mm), support point diameter 2 mm (± 0.02 mm).

The surface of the fixture is smooth and has no edges or corners.

5.3 Measurement tools

Vernier caliper: accuracy ± 0.02 mm.

Digital micrometer: accuracy ± 0.001 mm.

5.4 Environmental Control

Temperature: 10°C to 35°C, 20 $\pm$ 5°C recommended.

Humidity: 30%-80%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, dimensions 20 $\times$ 6.5 $\times$ 5.25 mm (± 0.05 mm), or adjusted according to the

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protocol.

The test surface should be flat and free of cracks, oxide layers or machining defects.

Surface roughness Ra <0.2 μm (polished).

The edges of the specimens were chamfered $0.1 \times 45^\circ$ to reduce stress concentration.

6.2 Number of samples

The number of samples in each batch shall not be less than 5 to ensure statistical representativeness.

If the result deviation is large (>5%), the number of samples needs to be increased to 10 .

6.3 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

7 Test steps

7.1 Equipment Calibration

The universal testing machine is calibrated using a standard force sensor with a load deviation of $\leq \pm 0.5\%$.

Check the accuracy of the fixture, the support point spacing deviation is $\leq \pm 0.05$ mm.

7.2 Test conditions

Ambient temperature: 10°C to 35°C, 20±5°C recommended.

Relative humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

Place the specimen in a three- or four-point bend fixture, making sure the specimen is level.

Loading speed: 0.5 mm/min (± 0.05 mm/min).

Slowly load until the specimen breaks and record the maximum breaking load F_F (N).

Use a vernier caliper or micrometer to measure the width of the specimen b and thickness h (accuracy ± 0.02 mm).

7.4 Result calculation

Calculate the transverse rupture strength according to the test type:

Three-point bending:

$$TRS = \frac{3FL}{2bh^2}$$

Four-point bending:

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$$TRS = \frac{3FL}{4bh^2} \times \frac{l_1}{l}$$

Take the average value of 5 samples , with a deviation of $\leq \pm 5\%$.

8 Evaluation of test results

8.1 Transverse rupture strength range

The transverse rupture strength of cemented carbide is usually 1500-3000 MPa, and the specific range depends on the grade and Co content:

YG6 (6% Co): 2000-2400 MPa.

YG8 (8% Co): 1800-2200 MPa.

YT15 (5% Co + TiC): 1600-2000 MPa.

8.2 Deviation Assessment

the 5 samples is $\leq \pm 5\%$, otherwise retesting is required.

If the TRS value exceeds the technical requirements of the grade, the cause needs to be analyzed (such as sample defects, uneven loading).

8.3 Analysis of influencing factors

Specimen quality: Surface roughness $R_a > 0.2 \mu m$ or edge chipping will result in low TRS (deviation $> 10\%$).

Loading speed: Speeds $> 1 \text{ mm/min}$ or $< 0.1 \text{ mm/min}$ will affect the breaking load (deviation $\pm 5\%$).

Fixture accuracy: Deviation of support point spacing $> 0.05 \text{ mm}$ or unevenness will cause stress concentration (deviation $> 5\%$).

Microstructure: Uneven WC grain size ($> \pm 0.2 \mu m$) or uneven Co phase distribution can lead to TRS fluctuations ($> \pm 6\%$).

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size, Co content.

Test conditions: equipment model, fixture type (three-point/four-point), loading speed (0.5 mm/min), ambient temperature (10°C to 35°C), humidity (30%-80%).

F of each specimen F , width b b b , thickness h h , TRS value and mean value, deviation.

Evaluation conclusion: whether it meets the technical requirements of the brand.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Transverse Fracture Strength of Typical Cemented Carbides

Brand	Co content (wt %)	Transverse rupture strength (MPa)	Grain size (μm)	Typical Applications
YG6	6	2000-2400	0.8-1.2	Mining drill bits

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Brand	Co content (wt %)	Transverse rupture strength (MPa)	Grain size (μm)	Typical Applications
YG8	8	1800-2200	0.8-1.2	Cutting Tools
YT15	5	1600-2000	0.6-1.0	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Appendix C (Informative Appendix) Comparison of three-point and four-point bending

parameter	Three-point bending	Four-point bending
Support span L L L	14.5 mm (±0.05 mm)	20 mm (±0.05 mm)
Loading point spacing l1 l1 l1 -		10 mm (±0.05 mm)
Stress distribution	Focus on the loading point	Uniform in loading range
Scope of application	Standard Tests	Complex stress analysis

Summarize

ISO 3327:2009 "Test Method for Compressive Strength of Cemented Carbide" (actually transverse rupture strength test) provides a standardized procedure for transverse rupture strength test of cemented carbide, and ensures the accuracy and repeatability of test results through standardized specimen preparation, test steps and result evaluation. The implementation of this standard helps the quality control and performance evaluation of cemented carbide, and provides reliable technical support for application fields such as cutting tools, mining drills, and molds.

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appendix:

ISO 28080:2021

Cemented Carbide Wear Test Method
Hardmetals — Abrasion tests for hardmetals

1 Scope

This standard specifies a general test method for determining the wear characteristics of cemented carbide. The test is suitable for laboratory environments where wear damage needs to be simulated. The test procedure includes test information under different conditions:

- a) using opposing wheels of different stiffness (such as steel wheels or rubber wheels);
- b) wet and dry testing;
- c) abrasives of different particle sizes;
- d) different chemical environments.

This standard is applicable to cemented carbides with tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase, and also to cemented carbides with the addition of other carbides (such as TaC, TiC, VC). This standard does not apply to coated cemented carbides or cemented carbides after surface strengthening (such as carburized layer wear test).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

ISO 3878:1983 Cemented carbide — Vickers hardness test

ISO 3611:2010 Cemented carbide — Terminology

ASTM G65-04(2010) Standard Test Method - Dry Sand /Rubber Wheel Abrasion Test

ASTM B611-13 Standard Test Method for High-Stress Wear Resistance of Hard Materials

ASTM G105-02(2013) Standard Test Method - Wet Sand/Rubber Wheel Abrasion Test

3 Terms and definitions

This standard adopts ISO 3611:2010 and the following terms and definitions:

Hardmetals: A composite material made of tungsten carbide (WC) as the main hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

Abrasion: Material loss caused by relative sliding of hard particles or rough surfaces.

Wear Rate: The volume or mass of material lost per unit time or unit sliding distance, expressed in mm^3/m or mg/m .

Counterface Wheel: The wheel that contacts the specimen and produces relative motion, which can be made of steel or rubber.

Abrasive: Hard particles such as quartz sand or aluminum oxide used to simulate wear.

4 Test Principle

Wear test is to contact the carbide specimen with the opposing wheel under specified conditions, apply a certain load and sliding distance, use abrasives (such as dry sand or wet sand) to simulate

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the wear environment, measure the mass loss or volume loss of the specimen, and calculate the wear rate. The test method refers to and supplements the ASTM G65 (dry sand /rubber wheel), ASTM B611 (high stress wear) and ASTM G105 (wet sand/rubber wheel) standards, and is applicable to different wear conditions.

5 Test equipment

5.1 Wear tester

Wear test device with adjustable load, load range 5-130 N, accuracy ± 0.5 N.

Sliding speed: 0.1-1 m/s, deviation $< \pm 0.05$ m/s.

Sliding distance: can be set up to 1000 m, accuracy ± 1 m.

5.2 Opposite wheels

Steel wheel: hardness HRC 55-60, diameter 228 mm (± 1 mm), width 12.7 mm (± 0.1 mm).

Rubber wheel: hardness Shore A 60-65, diameter 228 mm (± 1 mm), width 12.7 mm (± 0.1 mm).

5.3 Abrasive supply system

Abrasive: Quartz sand (particle size 200-300 μm) or aluminum oxide (particle size 100-200 μm), purity $> 98\%$.

Feed rate: 250-300 g/min, deviation $< \pm 5$ g/min (dry).

Wet test: water-based suspension, abrasive concentration 10-20 wt %.

5.4 Measurement tools

Precision balance: accuracy ± 0.1 mg.

Vernier caliper: accuracy ± 0.02 mm.

Surface profiler: measures wear depth with an accuracy of ± 0.001 mm.

5.5 Environmental Control

Temperature: 10°C to 35°C, 20 ± 5 °C recommended.

Humidity: 30%-80%, 50 $\pm 10\%$ recommended.

Controlled chemical environments (such as acidic or alkaline solutions).

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, dimensions 76 $\times$ 25.4 $\times$ 6.35 mm (± 0.1 mm), or adjusted according to the protocol.

The test surface should be flat and free of cracks, oxide layers or machining defects.

Surface roughness Ra < 0.2 μm (polished).

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

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If the result deviation is large (>10%), the number of samples needs to be increased to 5 .

6.3 Sample marking

The samples should be marked with batch number, brand (such as YG8, YT15) and test items, and the marking should not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

After the test, an ultrasonic cleaner (40 kHz, 5 min) was used to remove the residual abrasive.

6.5 Initial Measurement

Measure the initial mass (accuracy ± 0.1 mg) and thickness (accuracy ± 0.02 mm) of the sample.

7 Test steps

7.1 Equipment Calibration

The tester is calibrated using a standard load with a deviation of $< \pm 0.5$ N.

Check the condition of the opposing wheels to ensure that there is no wear or contamination on the surface.

7.2 Test conditions

Ambient temperature: 10°C to 35°C, 20 $\pm$ 5°C recommended.

Relative humidity: 30%-80%, 50 $\pm$ 10% recommended.

Chemical environment: Select according to the protocol (e.g., deionized water, 1% HCl).

7.3 Test operation

Mount the specimen on the tester, contact it with the opposite wheel, and apply a load (45 N is recommended).

Select test conditions:

Dry type: using steel wheel, feeding quartz sand 250 g/min, sliding distance 4300 m.

Wet type: using rubber wheels, feeding wet sand suspension, sliding distance 4300 m.

Start the tester and record the sliding distance and specimen wear.

Each sample was tested once and repeated 3-5 times to ensure the stability of the results.

7.4 Outcome Measurement

After testing, the specimens were cleaned, dried, and the final mass was measured (accuracy ± 0.1 mg).

The wear depth was measured using a surface profilometer (accuracy ± 0.001 mm).

Calculate the mass loss: $\Delta m = m_0 - m_1$ (m_0 is the initial mass, m_1 is the final mass).

7.5 Wear rate calculation

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Wear rate:

$$W = \frac{\Delta m}{L}$$

in:

W is the wear rate, in mg/m;

Δm is the mass loss, in mg;

L is the sliding distance in meters.

Or calculate the volume wear rate (need to combine density):

$$V = \frac{\Delta m}{\rho \cdot L}$$

in:

V is the volume wear rate, in mm³ / m;

ρ is the material density in g/ cm³ .

8 Evaluation of test results

8.1 Wear rate range

Carbide wear rates vary depending on test conditions and grade:

YG6 (6% Co): dry 0.5-1.0 mg/m, wet 0.3-0.7 mg/m.

YG8 (8% Co): dry type 0.7-1.2 mg/m³, wet type 0.5-0.9 mg/m³.

YT15 (5% Co + TiC): dry 0.4-0.8 mg/m, wet 0.2-0.6 mg/m.

8.2 Deviation Assessment

of 3-5 samples is $\leq \pm 10\%$, otherwise retesting is required.

If the wear rate exceeds the expected range, the cause needs to be analyzed (such as uneven abrasive particle size and surface defects of the specimen).

8.3 Analysis of influencing factors

Stiffness of opposing wheels: The wear rate of steel wheels is higher than that of rubber wheels (deviation > 20%).

Abrasive particle size: Particle sizes > 300 μm increase the wear rate (deviation > 15%).

Chemical environment: Acidic environments (such as 1% HCl) will accelerate corrosive wear (deviation > 30%).

Load: Loads > 130 N may cause the specimen to crack and affect the results.

9 Test Report

The test report should include the following:

Sample information: brand, batch number, size, Co content.

Test conditions: equipment model, opposing wheel type (steel/rubber), load (N), sliding distance (m), abrasive type and particle size, environment (wet/dry/chemical).

Test results: initial mass, final mass, mass loss, wear rate, wear depth and average value, deviation.

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Evaluation conclusion: whether it meets the expected range.

Test date and operator's signature.

Appendix A (Informative Appendix) Typical Carbide Wear Rate Reference Values

Brand	Co content (wt %)	Dry wear rate (mg/m)	Wet wear rate (mg/m)	Typical Applications
YG6	6	0.5-1.0	0.3-0.7	Mining drill bits
YG8	8	0.7-1.2	0.5-0.9	Cutting Tools
YT15	5	0.4-0.8	0.2-0.6	Finishing tools

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment (unless testing specific chemical environments).

Test bench levelness: deviation <0.02 mm/m.

Appendix C (Informative Appendix) Examples of wear test conditions

Test Type	Opposite wheel	Load(N)	Sliding distance (m)	Abrasive	environment
Dry	Steel wheels	45	4300	Quartz sand 250 μm	Air
Wet	Rubber wheel	45	4300	Wet sand 200 μm	water
Chemical	Steel wheels	45	2000	Quartz sand 250 μm	1% HCl

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appendix:

ASTM B611-13 Standard Test Method
— High stress wear resistance for hard materials

1 Scope

1.1 This standard test method is intended to test the high stress wear resistance of hard materials, primarily carbide, but also applicable to ceramics, cermets, and metal-based hard coatings with hardness exceeding 55 HRC. This method simulates high stress wear conditions in which the abrasive particles fracture by using a steel wheel to force the abrasive to contact the specimen, in contrast to low stress wear tests using rubber wheels (such as G65, G105, and G75 methods).

1.2 This test method uses an aqueous slurry containing aluminum oxide particles as the abrasive medium and forces the abrasive across the flat specimen surface by means of a rotating steel wheel in line contact with the rotating wheel which is immersed in the slurry.

1.3 Where units are given in inch-pound format , SI units are referenced and approximate equivalents are given in parentheses.

1.4 This standard does not attempt to cover all safety issues. It is the responsibility of the tester to establish appropriate safety and health practices for each specific situation and to evaluate the applicability of regulatory limitations.

1.5 This international standard has been prepared in accordance with the principles for the preparation of international standards, guidelines and recommendations of the World Trade Organization Technical Barriers to Trade Committee.

2 Significance and Use

2.1 Extraction of minerals from the earth's crust usually requires the use of metal tools to break rock. These tools are often covered, clad or coated with hard materials such as carbide. Drilling, breaking and moving rock causes high stress wear where the tool surface contacts the rock, with pressure sufficient to break the rock. This test method simulates these conditions and is used to screen new materials for such applications. It can also be used as a quality control tool for high stress wear applications such as slurry pumps, crushing equipment, recycling cutters, demolition equipment, etc.

2.2 Most wear tests use low stress wear, where the abrasive remains relatively intact during the test. High stress wear simulates an application scenario where the forces between the abrasive and the tool/part are large enough to crush the abrasive.

3 Terms and definitions

High stress wear: A type of wear in which the abrasive breaks under sufficient force, caused by the

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steel wheel forcing contact with the specimen.

Low stress wear: A type of wear in which the abrasive remains relatively intact during the test, usually caused by rubber wheels.

Wear Resistance: The ability of a material to resist wear, expressed as wear volume or mass loss.

4 Test equipment

4.1 Wear test device

Consists of a rotating steel wheel (228.6 mm diameter, 12.7 mm width) that rotates at 200 ± 10 rpm. The steel wheel material is hardened steel with a hardness of ≥ 60 HRC.

4.2 Abrasive

Alumina (Al_2O_3) particles with a particle size of 200-280 mesh were used to prepare an aqueous slurry with a volume concentration of 60%.

4.3 Specimen fixture

linear contact with the steel wheel and the loading force is 250 ± 5 N.

4.4 Environmental Control

Temperature: 15°C to 35°C , $23 \pm 2^\circ\text{C}$ recommended.

Humidity: 30% to 70%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

5. Sample requirements

5.1 Materials

Carbide, ceramic, cermet or metal based hard coatings with hardness > 55 HRC.

5.2 Dimensions

Specimen size: $50.8 \text{ mm} \times 25.4 \text{ mm} \times 6.35 \text{ mm}$ (length $\times$ width $\times$ height), tolerance $\pm 0.1 \text{ mm}$.

The surface is smooth, with a roughness of $R_a \leq 0.2 \mu\text{m}$.

5.3 Surface preparation

Use 600# to 1200# diamond sandpaper for grinding and $0.25 \mu\text{m}$ aluminum oxide polishing liquid for polishing.

5.4 Number of samples

three samples of each material were used for statistical analysis.

6 Test procedures

6.1 Equipment Preparation

Check the surface of the steel wheel for obvious wear or cracks and replace it if necessary.

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Adjust the specimen grips to ensure that the loading force is 250 ± 5 N.

6.2 Test operation

The specimen is fixed in the fixture in line contact with the steel wheel.

Add 200 mL of alumina slurry to the test apparatus.

Rotate the steel wheel at 200 ± 10 rpm for 600 revolutions (approximately 3 minutes).

After the test, take out the sample, clean it with anhydrous ethanol and dry it.

6.3 Measurement

The mass loss of the samples was measured using a precision balance (accuracy ± 0.001 g).

Record the initial mass m_1 and final mass m_2 , and calculate the mass loss $\Delta m = m_1 - m_2$.

6.4 Repeatability

Repeat the test twice for each sample and take the average value.

7 Result calculation

7.1 Wear rate

The wear rate is expressed as mass loss (g) or volume loss (mm^3).

The volume loss can be calculated by dividing the mass loss by the material density:

$$V = \frac{\Delta m}{\rho}$$

where ρ is the material density (g/cm^3).

7.2 Relative wear resistance

The mass loss of the specimen is compared with the mass loss of a reference material (such as standard cemented carbide) and the relative wear resistance is calculated.

7.3 Result evaluation

Ensure that the average mass loss deviation of the three samples is $< \pm 5\%$, otherwise retesting is required.

8 Influencing factors

8.1 Abrasive particle size: Particle size deviation from 200-280 mesh may result in a deviation of 5%-10% in the results.

8.2 Loading force: A force deviation from 250 ± 5 N may affect the wear rate by 3%-5%.

8.3 Steel wheel condition: Wheel surface wear may increase the test error by 2%-4%.

9 Test Report

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The test report should include the following:

Specimen information: material type, hardness, size.

Test conditions: wheel speed, loading force, abrasive type, ambient temperature (15°C to 35°C), humidity (30%-70%).

Test results: initial mass, final mass, mass loss, mean and deviation.

Relative wear resistance (if applicable).

Test date and operator signature.

Appendix A (Informative Appendix) Typical material wear reference values

Material Type	Hardness(HRC)	Mass loss (g)	Typical Applications
Cemented Carbide(YG6)	88	0.02-0.05	Mining drill bits
ceramics	75	0.05-0.10	Wear-resistant coating
Metal-based cladding	60	0.10-0.15	Crushing equipment

Appendix B (Informative Appendix) Environmental Requirements

Temperature: 15°C to 35°C, 23±2°C recommended.

Humidity: 30%-70%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

appendix:

ASTM E23-18

Notched specimen impact test method

Standard Test Methods for Notched Bar Impact Testing of Metallic Materials

1 Scope

This standard specifies the method for determining the impact absorption energy of notched specimens by Charpy or Izod impact tests at room temperature (10°C to 35°C) or low temperature (-196°C to 0°C) for metallic materials, including test principles, equipment requirements, specimen preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to metallic materials with different notch types (such as steel, cemented carbide, titanium alloy, etc.), but not to non-metallic materials or environments with temperatures exceeding 35°C.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all revisions) is applicable to this standard.

ASTM E4-21 Standard Practice for Calibration of Force, Compression, and Deformation Testing Machines

ASTM E23-16c Standard Test Method for Notched Specimen Impact Testing (Historical Version Reference)

ISO 148-1:2016 Metallic materials — Charpy pendulum impact test Part 1: Test method

ASTM E2298-19 Standard Test Method - Instrumented Impact Testing

3 Terms and definitions

This standard adopts ASTM E23-18 and the following terms and definitions:

Impact Energy: The energy absorbed by the notched specimen in the impact test, measured in joules (J), reflects the impact toughness of the material.

Charpy test: A test that uses a cantilever beam specimen to measure energy absorption by pendulum impact.

Izod test: A test to determine energy absorption by pendulum impact using a single-support beam specimen.

Notch Type: Pre-made notch shapes on the specimen include V-notch (2 mm deep, 45° angle, 0.25 mm root radius) and U-notch (5 mm deep, 1 mm root radius).

4 Test Principle

The impact test releases a pendulum from a specified height to impact a pre-notched metal specimen, measures the remaining kinetic energy (or energy loss) after the pendulum breaks the specimen, and calculates the impact energy absorbed by the specimen. This energy reflects the toughness and fracture behavior of the material under high-speed loading. The test is applicable to Charpy or Izod configurations, and the specific formula is:

$$E = mgh - mgh'$$

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in:

E is the impact absorption energy, in J;

m is the mass of the pendulum, in kg;

g is the acceleration due to gravity, about 9.81 m/s^2 ;

h is the initial height, in meters;

h' is the remaining height after fracture, in meters (usually measured indirectly by the pendulum angle).

5 Test equipment

5.1 Impact testing machine

Pendulum impact tester with energy range of 150 J to 750 J, accuracy of $\pm 1 \text{ J}$, calibrated to ASTM E4-21.

Pendulum release height: adjustable, initial angle 150° .

5.2 Specimen fixture

Charpy fixture: support span 40 mm ($\pm 0.05 \text{ mm}$), support surface flatness $< 0.01 \text{ mm}$.

Izod clamp: single support, height 28 mm ($\pm 0.05 \text{ mm}$), uniform clamping force.

5.3 Measurement tools

Vernier caliper: accuracy $\pm 0.02 \text{ mm}$, used to measure sample size.

Angle measuring device: accuracy $\pm 0.1^\circ$, used to calibrate the pendulum position.

5.4 Cryogenic equipment (optional)

Liquid nitrogen or dry ice cooling box, temperature range -196°C to 0°C , accuracy $\pm 2^\circ\text{C}$.

5.5 Environmental Control

Temperature: 10°C to 35°C (room temperature), or -196°C to 0°C (cold temperature), $20 \pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Specimen type

Charpy specimen: size $55 \times 10 \times 10 \text{ mm}$ ($\pm 0.1 \text{ mm}$), notch in the center.

Izod specimen: Dimensions: $75 \times 10 \times 10 \text{ mm}$ ($\pm 0.1 \text{ mm}$), notch located 28 mm from one end.

6.2 Gap preparation

V-notch: depth 2 mm ($\pm 0.025 \text{ mm}$), angle 45° ($\pm 0.5^\circ$), root radius 0.25 mm ($\pm 0.025 \text{ mm}$).

U-shaped notch: depth 5 mm ($\pm 0.025 \text{ mm}$), root radius 1 mm ($\pm 0.025 \text{ mm}$).

The notch surface is smooth and burr-free, prepared by wire cutting or milling.

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6.3 Sample requirements

The surface of the specimen is smooth, without cracks, oxide layer or processing defects.

Surface roughness $R_a < 0.2 \mu\text{m}$ (polished).

The edges of the specimens were chamfered $0.1 \times 45^\circ$ to reduce stress concentration.

6.4 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large ($>10 \text{ J}$), the number of samples needs to be increased to 5.

6.5 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

6.6 Sample marking

The specimens should be marked with batch number, grade (such as YG8, 1045 steel) and test items, and the marking should not affect the test area.

6.7 Low temperature treatment (optional)

Place the sample in a cooling box and maintain the specified temperature for 15-30 min to ensure uniform cooling.

7 Test steps

7.1 Equipment Calibration

The impact tester is calibrated using a standard pendulum with an energy deviation of $< \pm 1 \text{ J}$.

Check the fixture and notch dimensions, the deviation is $< \pm 0.025 \text{ mm}$.

7.2 Test conditions

Ambient temperature: 10°C to 35°C (room temperature), or -196°C to 0°C (low temperature), $20 \pm 5^\circ\text{C}$ is recommended.

Relative humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

Mount the specimen in the fixture (Charpy or Izzy configuration) ensuring that the notch faces the direction of the pendulum impact.

Release the pendulum and record the impact energy E (J).

Each sample was tested once and repeated 3-5 times to ensure the stability of the results.

If low temperature testing is carried out, the specimen shall be tested immediately ($< 5 \text{ s}$) after being taken out of the cooling box.

7.4 Fracture surface observation (optional)

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The fracture surfaces were observed using an optical microscope (magnification 50×) and the fracture type (brittle or ductile) was recorded.

8 Evaluation of test results

8.1 Impact absorption energy range

Impact absorption energy range of metal materials: 5-200 J, the specific value depends on the material and temperature:

Cemented carbide (YG8, room temperature): 10-20 J.

Hardened steel (1045, room temperature): 50-80 J.

Aluminum alloy (6061-T6, room temperature): 20-40 J.

At low temperatures (-40°C), energy is typically reduced by 20%-50%.

8.2 Deviation Assessment

of 3-5 specimens is $< \pm 10$ J, otherwise retesting is required.

If the energy value exceeds the material technical requirements, the reasons (such as notch quality, sample defects) need to be analyzed.

8.3 Analysis of influencing factors

Notch quality: Notch root radius error > 0.025 mm or surface roughness > 0.2 μ m will reduce energy (deviation $> 15\%$).

Temperature: A temperature decrease of $> 20^{\circ}\text{C}$ will significantly reduce energy (deviation $> 30\%$).

Loading speed: A deviation of the pendulum speed > 0.05 m/s will affect the results (deviation $\pm 5\%$).

Microstructure: Uneven grain size ($> \pm 0.2$ μ m) or high porosity will reduce toughness (deviation $> 10\%$).

9 Test Report

The test report should include the following:

Sample information: material type, brand, batch number, size, notch type (V/U).

Test conditions: equipment model, fixture type (Charpy/Izod), test temperature ($^{\circ}\text{C}$), ambient humidity (30%-80%).

Test results: Impact absorption energy E of each sample E (J), mean value and deviation, fracture type (if observed).

Evaluation conclusion: whether it meets the technical requirements of the material.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference values of impact energy of typical metal materials

Material Type	Brand/category	Impact energy (J, room temperature)	Impact energy (J, -40°C)	Typical Applications
Cemented	YG8	10-20	5-10	Cutting Tools

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Material Type	Brand/category	Impact energy (J, room temperature)	Impact energy (J, -40°C)	Typical Applications
Carbide				
Hardened steel	1045 (HRC 30)	50-80	20-40	Mechanical parts
Aluminum Alloy	6061-T6	20-40	10-20	Aerospace structures

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C (room temperature), or -196°C to 0°C (cold temperature), 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Appendix C (Informative Appendix) Relationship between gap size and energy

Gap Type	Depth(mm)	Angle (°)	Root radius(mm)	Energy impact (%)
V-type	2	45	0.25	Benchmarks
U shape	5	0	1.0	Increase by 10%-20%

Summarize

ASTM E23-18 "Notched Specimen Impact Test Method" provides a standardized procedure for the impact toughness test of metal materials, and ensures the accuracy and repeatability of the test results through standardized specimen preparation, test steps and result evaluation. The implementation of this standard helps to evaluate the impact performance of metal materials (such as cemented carbide and steel) and provides reliable technical support for application fields such as machinery manufacturing, construction, and energy.

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appendix:

ASTM G65-16

Dry Sand /Rubber Wheel Wear Test Method Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus

1 Scope

This standard specifies the laboratory method for measuring the scratch wear resistance of metal materials through dry sand /rubber wheel test , including test principles, equipment requirements, sample preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to the wear resistance test of metal materials (including cemented carbide, steel, alloy, etc.), and aims to generate repeatable material scratch wear resistance ranking data under specific conditions. This standard is not applicable to non-metallic materials or attempts to fully simulate actual working conditions (such as corrosive environments or impact conditions).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all revisions) is applicable to this standard.

ASTM E4-21 Standard Practice for Calibration of Force, Compression, and Deformation Testing Machines

ASTM G105-02(2013) Standard Test Method - Wet Sand/Rubber Wheel Abrasion Test

ASTM B611-13 Standard Test Method for High Stress Wear Resistance of Cemented Carbides

3 Terms and definitions

This standard adopts ASTM G65-16 and the following terms and definitions:

Scratching Abrasion: Material loss caused by relative sliding of hard particles on the material surface under a certain pressure.

Volume Loss: The volume of material lost by the specimen after the wear test, in cubic millimeters (mm^3) .

Wear Rate: The volume of material lost per unit sliding distance, expressed in mm^3 / m .

Counterface Wheel : A rubber wheel that contacts the specimen and produces relative motion, with a hardness of Shore A 60-65 .

Abrasive: Hard particles used to simulate wear, which in this standard refers to dry sand (such as quartz sand).

4 Test Principle

dry sand /rubber wheel wear test evaluates the wear resistance of the material by contacting the metal specimen with a rotating rubber wheel in a dry sand abrasive environment , applying a certain load and sliding distance, and measuring the mass or volume loss of the specimen due to scratch wear. The test conditions are standardized to ensure the repeatability of the results, and the test results are reported in volume loss (mm^3) . Materials with higher wear resistance have lower volume loss.

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5 Test equipment

5.1 Wear tester

dry sand/rubber wheel device with adjustable load , load range 5-130 N, accuracy ± 0.5 N.

Sliding speed: 0.1-1 m/s, deviation $< \pm 0.05$ m/s.

Sliding distance: can be set up to 4300 m, accuracy ± 1 m.

5.2 Rubber Wheel

Hardness: Shore A 60-65.

Diameter: 228 mm (± 1 mm), width 12.7 mm (± 0.1 mm).

The surface is free of defects and needs to be replaced regularly to ensure consistency.

5.3 Abrasive supply system

Abrasive: dry quartz sand, particle size 200-300 μm , purity $> 98\%$.

Feed rate: 250-300 g/min, deviation $< \pm 5$ g/min.

The sand flow is evenly distributed through a standard geometry nozzle (width 1 mm).

5.4 Measurement tools

Precision balance: accuracy ± 0.1 mg.

Vernier caliper: accuracy ± 0.02 mm.

Surface profiler: measures wear depth with an accuracy of ± 0.001 mm.

5.5 Environmental Control

Temperature: 10°C to 35°C, 20 ± 5 °C recommended.

Humidity: 30%-80%, 50 $\pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, dimensions 76 $\times$ 25.4 $\times$ 6.35 mm (± 0.1 mm), or adjusted according to the protocol.

The test surface should be flat and free of cracks, oxide layers or machining defects.

Surface roughness Ra < 0.2 μm (polished).

6.2 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large ($> 10\%$), the number of samples needs to be increased to 5 .

6.3 Sample marking

The specimens shall be marked with the batch number, grade (such as YG8, AISI 1020 steel) and

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test item, and the marking shall not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol to remove oil, dust, and use it after drying.

After the test, an ultrasonic cleaner (40 kHz, 5 min) was used to remove the residual abrasive.

6.5 Initial Measurement

Measure the initial mass (accuracy ± 0.1 mg) and thickness (accuracy ± 0.02 mm) of the sample.

7 Test steps

7.1 Equipment Calibration

The tester is calibrated using a standard load with a deviation of $< \pm 0.5$ N.

Check the condition of the rubber wheel to ensure that the surface is not worn or contaminated.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 5^{\circ}\text{C}$ recommended.

Relative humidity: 30%-80%, $50 \pm 10\%$ recommended.

Test environment: dry, without liquid medium.

7.3 Test operation

This standard provides five test procedures (A, B, C, D, E), selected according to the wear resistance of the material:

Procedure A: High wear test, load 130 N, wheel speed 200 rpm, sliding distance 4300 m, suitable for medium to high wear resistant materials.

Program B: Short-time variant, load 130 N, wheel speed 200 rpm, sliding distance 718 m, suitable for materials with low and medium wear resistance (use when volume loss > 100 mm³).

Program C: Short-time variant, load 130 N, wheel speed 200 rpm, sliding distance 71.8 m, suitable for thin coatings.

Program D: Light-duty variant, load 45 N, wheel speed 200 rpm, sliding distance 4300 m, suitable for materials with low wear resistance.

Program E: Short-time variant, load 45 N, wheel speed 200 rpm, sliding distance 718 m, suitable for materials with low and medium wear resistance.

The specimen is mounted on the tester, in contact with the rubber wheel, and the load is applied.

Start the tester and record the sliding distance and specimen wear.

Each sample was tested once and repeated 3-5 times to ensure the stability of the results.

7.4 Outcome Measurement

After testing, the specimens were cleaned, dried, and the final mass was measured (accuracy ± 0.1 mg).

The wear depth was measured using a surface profilometer (accuracy ± 0.001 mm).

Calculate the mass loss: $\Delta m = m_0 - m_1$ (m_0 is the initial mass, m_1 is the final mass).

7.5 Volume loss calculation

Volume loss:

$$V = \frac{\Delta m}{\rho}$$

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in:

V is the volume loss in mm³ ;

Δm is the mass loss, in mg;

ρ is the material density in g/ cm³ .

Wear rate:

$$W = \frac{V}{L}$$

in:

W is the wear rate in mm³ / m;

L is the sliding distance in meters.

8 Evaluation of test results

8.1 Volume loss range

The range of volume loss in metallic materials varies by procedure and material:

Cemented carbide (YG8, procedure A): 10-20 mm³ .

Mild steel (AISI 1020, Procedure A): 50-100 mm³ .

Highly wear-resistant materials (Procedure B): 5-15 mm³ .

8.2 Deviation Assessment

of 3-5 samples is <±10%, otherwise retesting is required.

If the volume loss exceeds the expected range, the cause needs to be analyzed (such as uneven abrasive particle size and surface defects of the specimen).

8.3 Analysis of influencing factors

Abrasive particle size: Particle sizes > 300 μm will increase volume loss (deviation > 15%).

Load: Loads > 130 N may cause the specimen to crack and affect the results.

Rubber wheel hardness: Hardness > Shore A 65 will increase wear (deviation > 10%).

Microstructure: Uneven grain size (>±0.2 μm) or high porosity will increase volume loss (deviation >10%).

9 Test Report

The test report should include the following:

Sample information: material type, brand, batch number, size.

Test conditions: Equipment model, procedure type (A/B/C/D/E), load (N), sliding distance (m), abrasive type and particle size, ambient temperature (10°C to 35°C), humidity (30%-80%).

Test results: initial mass, final mass, mass loss, volume loss (mm³) , wear rate (mm³ / m), wear depth and average value, deviation.

Evaluation conclusion: whether it meets the expected range.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference Values of Volume Loss of Typical Metal

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Materials

Material Type	Brand/category	Procedure A Volume loss (mm ³)	Procedure B Volume loss (mm ³)	Typical Applications
Cemented Carbide	YG8	10-20	5-10	Cutting Tools
Mild Steel	AISI 1020	50-100	20-40	Structural parts
High wear resistant coating	WC-10Co-4Cr	5-15	2-8	Mining Equipment

Appendix B (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

Appendix C (Informative Appendix) Comparison of test procedures

program	Load(N)	Sliding distance (m)	Scope of application
A	130	4300	Medium to high wear resistant materials
B	130	718	Medium and low wear resistance materials
C	130	71.8	Thin coating
D	45	4300	Low wear resistance material
E	45	718	Medium and low wear resistance materials

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appendix:

EN ISO 6507-1:2018

Vickers hardness test

Metallic materials

— Vickers hardness test — Part 1: Test method

1 Scope

This standard specifies the method for determining the hardness of metallic materials by Vickers hardness test at room temperature (10°C to 35°C), including test principle, equipment requirements, specimen preparation, test steps, result calculation and evaluation, test report, etc. This standard is applicable to the test of Vickers hardness range HV 1 to HV 3000, covering different loads (0.098 N to 2942 N). This standard is not applicable to the hardness test of tiny or thin-walled specimens (thickness <0.1 mm) or coated materials.

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard. EN ISO 6507-2:2018 Metallic materials — Vickers hardness test Part 2: Verification and calibration of hardness testers

EN ISO 6507-3:2018 Metallic materials — Vickers hardness test Part 3: Calibration standards

EN ISO 376:2011 Metallic materials — Calibration force standards

EN ISO 18265:2013 Metallic materials — Conversion between hardness and strength

3 Terms and definitions

This standard adopts EN ISO 6507-1:2018 and the following terms and definitions:

Vickers Hardness (HV): The ability of a metal material to resist the penetration of a Vickers indenter, expressed as a Vickers hardness value in N/mm² (or MPa), calculated by the diagonal length of the indentation.

Vickers indenter: A square diamond pyramid indenter with a vertex angle of 136°.

Indentation diagonal: The length of the two diagonals of the square indentation formed when the Vickers indenter is pressed into the sample surface, in mm.

Test Load (F): The force applied to the Vickers indenter in Newtons (N), ranging from 0.098 N to 2942 N.

Holding time : The time the load is maintained after the indenter applies the load, in seconds (s).

4 Test Principle

The Vickers hardness test is carried out by pressing a standard Vickers diamond indenter (vertex angle 136°) into the surface of a metal sample with a specified load, holding it for a certain period of time and then unloading it, measuring the length of the two diagonals of the indentation (d1, d2), calculating the average diagonal length (d), and then calculating the Vickers hardness value (HV).

The calculation formula is:

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$$HV = \frac{1.8544 \times F}{d^2} \quad \text{in:}$$

F is the test load, in N;

d 为压痕两条对角线的平均长度, 单位为 mm, $d = \frac{d_1 + d_2}{2}$;

The unit of hardness is N/mm² (1 kgf / mm² $\approx$ 9.807 N/mm²).

5 Test equipment

5.1 Vickers hardness tester

Complies with EN ISO 6507-2:2018 verification and calibration requirements.

Load range: 0.098 N to 2942 N (HV 0.01 to HV 30), accuracy $\pm 0.5\%$.

Holding time control: 5 s to 60 s, deviation $\leq \pm 0.5$ s.

5.2 Pressure head

Standard Vickers diamond indenter, vertex angle 136° ($\pm 0.5^\circ$).

The surface of the indenter is free of defects and has clear edges (microscope inspection, resolution $< 0.5 \mu\text{m}$).

5.3 Measurement device

Optical microscope: magnification 50×-1000×, 400× recommended, resolution $< 0.5 \mu\text{m}$.

Equipped with a digital readout system with a measurement accuracy of ± 0.001 mm.

5.4 Calibration Block

Standard calibration blocks in accordance with EN ISO 6507-3:2018, hardness range HV 100-3000, deviation $\leq \pm 2\%$.

The surface roughness of the calibration block is Ra $< 0.05 \mu\text{m}$.

5.5 Environmental Control

Temperature: 10°C to 35°C, 20 $\pm$ 5°C recommended.

Humidity: 30%-80%, 50 $\pm$ 10% recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

6.1 Sample requirements

Specimen shape: cuboid, cylinder or other regular geometric shape, test surface area $> 5 \times 5$ mm, thickness > 0.5 mm (load dependent).

The test surface should be flat and free of cracks, oxide layers or machining defects.

Surface roughness Ra $< 0.1 \mu\text{m}$ (polished), for low load (< 9.807 N) testing, Ra $< 0.05 \mu\text{m}$.

The thickness of the specimen should meet the following requirements: thickness $\geq 1.5 \times$ diagonal length of the indentation.

6.2 Number of samples

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The number of samples in each batch shall not be less than 3 to ensure statistical representativeness. If the result deviation is large ($>3\%$), the number of samples needs to be increased to 5.

6.3 Sample marking

The specimens shall be marked with batch number, grade (such as YG8, S235JR steel) and test item, and the marking shall not affect the test area.

6.4 Sample cleaning

Before testing, clean the surface of the sample with anhydrous ethanol or acetone to remove oil, dust, and use it after drying.

7 Test steps

7.1 Equipment Calibration

Use the standard calibration block to calibrate the hardness tester. Select the calibration block that matches the test load. Measure 3 times. The hardness deviation is $<\pm 1\%$. Check the condition of the indenter to ensure there is no wear or defects.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20\pm 5^{\circ}\text{C}$ recommended.

Relative humidity: 30%-80%, $50\pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Load selection

Select the load based on the material hardness and specimen thickness:

Carbide: 294.2 N (30 kgf, HV 30) is recommended.

Steel: 50 N to 294.2 N (HV 5 to HV 30).

Thin-walled specimens: 0.098 N to 9.807 N (HV 0.01 to HV 1).

The load should ensure that the diagonal length d of the indentation is in the range 0.020 mm to 1.400 mm.

7.4 Test operation

Place the specimen on the hardness tester workbench, making sure the test surface is level.

Select an appropriate load (e.g. 294.2 N) and hold the load for 10-15 s (or adjust according to material requirements).

The indenter is slowly pressed into the sample surface and automatically unloaded after maintaining the load.

5 indentation points shall be measured for each specimen, with the indentation spacing > 3 times the diagonal length (> 0.3 mm) and the distance from the specimen edge to > 0.5 mm.

7.5 Measurement and calculation

The lengths of the two diagonal lines of the indentation (d_1 , d_2) were measured using an optical

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microscope with an accuracy of ± 0.001 mm.

Calculate the average diagonal length:

$$d = \frac{d_1 + d_2}{2}$$

Calculate Vickers hardness:

$$HV = \frac{1.8544 \times F}{d^2}$$

five indentation points is taken as the hardness value of the sample, with a deviation of $< \pm 3\%$.

8 Evaluation of test results

8.1 Hardness value range

Vickers hardness range of metal materials: HV 100-3000, the specific value depends on the material :

Cemented carbide (YG8): HV 1450-1550.

Hardened steel (42CrMo4): HV 500-700.

Aluminum alloy (6082-T6): HV 50-150.

8.2 Deviation Assessment

the 5 indentation points is $< \pm 3\%$, otherwise retesting is required.

If the hardness value exceeds the material technical requirements, the cause needs to be analyzed (such as surface defects, load mismatch).

8.3 Analysis of influencing factors

Load selection: If the load is too low (< 0.098 N), a clear indentation may not be formed; if the load is too high (> 2942 N), the specimen may be deformed.

Surface quality: Surface roughness $R_a > 0.1 \mu\text{m}$ will result in lower hardness values (deviation $> 5\%$).

Holding time : A time < 5 s or > 60 s will affect the indentation size (deviation $\pm 2\%$).

Specimen thickness: Thickness $< 1.5 \times$ indentation diagonal length will lead to support effect and high hardness value (deviation $> 10\%$).

9 Test Report

The test report should include the following:

Sample information: material type, brand, batch number, size.

Test conditions: equipment model, load (N), holding time (s), ambient temperature (10°C to 35°C), humidity (30%-80%).

Test results: average diagonal length of each indentation (d), hardness value (HV), average hardness value and deviation.

Evaluation conclusion: whether it meets the technical requirements of the material.

Test date and operator's signature.

Appendix A (Informative Appendix) Vickers hardness reference values for typical metal materials

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Material Type	Brand/category	Vickers hardness (HV)	Typical load (N)	Typical Applications
Cemented Carbide	YG8	1450-1550	294.2	Cutting Tools
Hardened steel	42CrMo4	500-700	294.2	Mechanical parts
Aluminum Alloy	6082-T6	50-150	9.807	Aerospace structures
cast iron	EN-GJL-250	200-300	98.07	Engine block

Appendix B (Informative Appendix) Table of the relationship between Vickers hardness and load

Load(N)	Hardness symbol	Diagonal length range of indentation (mm)	Applicable Materials
0.098	HV 0.01	0.020-0.050	Thin wall or small specimens
9.807	HV 1	0.050-0.150	Soft metals (such as aluminum)
98.07	HV 10	0.150-0.400	Medium hard materials (such as cast iron)
294.2	HV 30	0.400-1.000	Hard alloy, steel
2942	HV 300	1.000-1.400	Superhard materials

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

EN ISO 6507-1:2018 "Metallic materials - Vickers hardness test" provides a standardized procedure for Vickers hardness testing of metallic materials, ensuring the accuracy and repeatability of test results through standardized specimen preparation, test steps and result evaluation. The implementation of this standard is applicable to the quality control and performance evaluation of materials such as cemented carbide, steel, and aluminum alloys, providing reliable technical support for application fields such as machinery manufacturing, aerospace, and mold manufacturing.

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appendix:

EN ISO 18265:2013

Metal materials - Conversion between hardness and strength

Metallic materials — Conversion of hardness values

1 Scope

This standard specifies the conversion method between different hardness test methods and between hardness values and tensile strength of metal materials. This standard is applicable to iron-based metals (such as carbon steel, alloy steel, stainless steel) and non-ferrous metals (such as aluminum, copper and their alloys). The conversion method is based on empirical data and is applicable to hardness values measured at room temperature (10°C to 35°C). This standard is not applicable to the hardness conversion of cemented carbides (such as WC-Co), superhard materials (such as diamond) or surface hardening materials (such as carburizing steel).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

EN ISO 6506-1:2014 Metallic materials — Brinell hardness test Part 1: Test method
EN ISO 6507-1:2018 Metallic materials — Vickers hardness test Part 1: Test method
EN ISO 6508-1:2016 Metallic materials — Rockwell hardness test Part 1: Test method
EN ISO 4545-1:2017 Metallic materials — Knoop hardness test Part 1: Test method
EN ISO 6892-1:2019 Metallic materials — Tensile testing Part 1: Test method at room temperature

3 Terms and definitions

This standard adopts EN ISO 18265:2013 and the following terms and definitions:

Hardness: The ability of a metal material to resist the penetration of an indenter, measured using different methods (such as Vickers, Brinell, Rockwell, and Knoop).

Tensile Strength (Rm): The maximum stress that a metal material can withstand in a tensile test, measured in MPa.

Conversion: The process of converting one hardness value to another hardness value or tensile strength based on empirical relationships.

Vickers hardness (HV): The hardness value measured by the Vickers hardness test, the unit is N/mm².

Brinell hardness (HBW): The hardness value measured by the Brinell hardness test, the unit is HBW (carbide ball indenter).

Rockwell hardness (HR): The hardness value measured by the Rockwell hardness test. Common scales are HRC, HRB, and HRA.

4 Conversion principle

The conversion between hardness and hardness or between hardness and tensile strength is based on empirical data and regression analysis. The conversion relationship varies depending on the material type, heat treatment state, and microstructure (such as grain size, phase distribution). This

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standard provides conversion tables and formulas, but the conversion results are only approximate values and the deviation may be as high as $\pm 10\%$. The following factors should be considered when converting:

Material category: iron-based metals (such as carbon steel, alloy steel) or non-ferrous metals (such as aluminum, copper).

Hardness range: Different hardness test methods have applicable ranges (such as HRC 20-70).

Test conditions: hardness test load, holding time, and sample surface quality.

5 Conversion conditions

5.1 Scope of application

Iron-based metals: carbon steel, alloy steel, stainless steel.

Non-ferrous metals: aluminum and aluminum alloys, copper and copper alloys.

Hardness range:

Vickers hardness (HV): 100-1000.

Brinell hardness (HBW): 100-700.

Rockwell hardness (HRC): 20-70.

Tensile strength (Rm): 300-2000 MPa.

5.2 Restrictions

Not suitable for cemented carbide (such as WC-Co) and superhard materials (such as diamond).

Not suitable for surface hardening materials (such as carburizing and nitriding layers).

It is not suitable for materials with abnormal microstructure (such as severe segregation and high porosity).

The conversion deviation may be up to $\pm 10\%$ and is for reference only.

5.3 Test requirements

The hardness test should comply with relevant standards (such as EN ISO 6507-1:2018).

The surface roughness of the specimen is $R_a < 0.1 \mu\text{m}$ and the thickness is $\geq 1.5 \times$ the diagonal length of the indentation.

Ambient temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

6 Conversion method

6.1 Conversion between hardnesses

is done through the tables provided in the standard. Some examples are as follows:

HRC to HV:

HRC 30 $\approx$ HV 320

HRC 50 $\approx$ HV 550

HRC 30 $\approx$ HV 320

HRC 50 $\approx$ HV 550

HV to HBW (Carbon Steel):

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HV 200 $\approx$ HBW 190

HV 500 $\approx$ HBW 475

HV 200 $\approx$ HBW 190
HV 500 $\approx$ HBW 475

6.2 Conversion between hardness and tensile strength

The conversion is completed through the tables or formulas provided by the standard. Some examples are as follows:

HRC to R_m (hardened steel):

HRC 30 $\approx R_m$ 900

MPaHRC 50 $\approx R_m$ 1500

HRC 30 $\approx R_m$ 900 MPa
HRC 50 $\approx R_m$ 1500 MPa

HBW to R_m (carbon steel, not heat treated):

$R_m \approx 3.3 \times \text{HBW}$ (HBW 100-400)

HBW 200 $\approx R_m$ 660 MPa

$R_m \approx 3.3 \times \text{HBW}$ (HBW 100-400)
HBW 200 $\approx R_m$ 660 MPa

6.3 Structure of the conversion table

Table A: Conversion of hardness of iron- based metals (carbon steel, alloy steel).

Table B: Stainless steel hardness conversion.

Table C: Hardness conversion of nonferrous metals (aluminum, copper).

Table D: Conversion between hardness and tensile strength.

7 Evaluation of conversion results

7.1 Deviation Analysis

Hardness conversion deviation: $\pm 5\%$ -10%, depending on the material and hardness range.

Conversion deviation between hardness and tensile strength: $\pm 10\%$ -15%, depending on the heat treatment status.

7.2 Influencing factors

Microstructure: Uneven grain size ($> \pm 0.2 \mu\text{m}$) or uneven phase distribution can lead to large deviations ($> 10\%$).

Heat treatment status: The conversion deviation of quenched and tempered steel and annealed steel is different ($\pm 5\%$ -15%).

Test conditions: The load, holding time and sample surface quality of the hardness test will affect the conversion accuracy.

7.3 Recommendations

Direct testing (such as tensile testing) to obtain tensile strength is preferred over conversion.

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The conversion result is for reference only and needs to be verified when necessary (when the deviation is >10%).

8 Conversion Report

The conversion report should include the following:

Material information: material type, grade, heat treatment status.

Hardness test information: test method (such as Vickers), load (N), hardness value and deviation.

Conversion results: target hardness value or tensile strength value, conversion basis (table number).

Deviation assessment: conversion deviation range and analysis of influencing factors.

Report date and operator signature.

Appendix A (Normative Appendix) Conversion Table of Hardness of Iron-Based Metals (Partial Examples)

HRC	HV	HBW	HRA	Applicable Materials
20	240	228	60	Mild Steel
30	320	304	67	Medium Carbon Steel
40	420	400	73	Hardened steel
50	550	525	78	High Strength Steel

Appendix B (Normative Appendix) Stainless Steel Hardness Conversion Table (Partial Examples)

HRC	HV	HBW	Applicable Materials
20	250	238	Austenitic stainless steel
30	330	315	Martensitic stainless steel
40	430	410	Precipitation Hardening Stainless Steel

Appendix C (Normative Appendix) Nonferrous Metal Hardness Conversion Table (Partial Examples)

HBW	HV	Applicable Materials
50	55	Pure aluminum
100	110	Aluminum alloy (such as 6061)
150	165	brass

Appendix D (Normative Appendix) Conversion table of hardness and tensile strength (some examples)

HBW	R _m	R _m (MPa)	Applicable Materials
150	495		Unheat treated carbon steel
200	660		Unheat treated carbon steel

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HBW	Rm R _m (MPa)	Applicable Materials
300	1000	Quenched and tempered steel

Appendix E (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Summarize

EN ISO 18265:2013 "Metallic materials - Conversion between hardness and strength" provides a standardized procedure for the conversion of hardness values of metallic materials, and ensures the reliability and consistency of the conversion results by providing detailed conversion tables and conditions. The implementation of this standard helps material engineers to make approximate assessments of hardness and strength in the absence of direct testing conditions, and is suitable for material performance analysis in the fields of machinery manufacturing, construction, energy, etc.

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appendix:

EN ISO 6892-1:2019

Tensile testing of metal materials

Metallic materials — Tensile testing

— Part 1: Method of test at room temperature

1 Scope

This standard specifies the method of tensile testing of metal materials at room temperature (10°C to 35°C) to determine their mechanical properties, including yield strength, tensile strength, elongation after fracture, cross-sectional shrinkage, etc. This standard is applicable to bars, plates, pipes, wires and processed parts of various metal materials (such as steel, aluminum alloy, copper alloy, etc.). This standard is not applicable to tests with temperatures exceeding the range of 10°C to 35°C, nor is it applicable to tests of micro-sized specimens (such as thickness <0.1 mm).

2 Normative references

The clauses in the following documents become clauses of this standard through reference in this standard. For dated referenced documents, only the referenced version is applicable. For undated referenced documents, the latest version (including all amendments) is applicable to this standard.

EN ISO 7500-1:2018 Metallic materials — Tension and compression testing machines Part 1: Calibration force standard devices

EN ISO 9513:2012 Metallic materials — Calibration of extensometer systems

EN ISO 377:2017 Steel and steel products — Sampling and preparation of test specimens for tensile testing

EN ISO 148-1:2016 Metallic materials — Charpy pendulum impact test Part 1: Test method

EN ISO 18265:2013 Metallic materials — Conversion between hardness and strength

3 Terms and definitions

This standard adopts EN ISO 6892-1:2019 and the following terms and definitions:

Yield strength (R_p) or specified plastic extension strength ($R_{p0.2}$): The stress at which the specimen undergoes specified plastic deformation during tension, expressed in MPa.

Tensile strength (R_m): The maximum stress that a specimen withstands during tension, expressed in MPa.

Elongation after fracture (A): The percentage of plastic elongation of the gauge length section after the specimen breaks to the original gauge length, expressed in %.

Sectional shrinkage (Z): The percentage of the reduction in cross-sectional area after the specimen breaks to the original cross-sectional area, expressed in %.

Gauge length (L_0): The initial length of the specimen used to measure elongation, in mm.

4 Test Principle

The tensile test applies a uniaxial tensile load to the metal sample on a universal testing machine until the sample breaks, records the load-displacement curve, and calculates the mechanical properties parameters (such as yield strength, tensile strength, elongation, etc.). The test process is divided into the elastic stage, yield stage, uniform plastic deformation stage, and necking fracture

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stage. The mechanical properties calculation formula is as follows:

屈服强度或规定塑性延伸强度:

$$R_p = \frac{F_p}{A_0}$$

抗拉强度:

$$R_m = \frac{F_m}{A_0}$$

断后延伸率:

$$A = \frac{L_u - L_0}{L_0} \times 100$$

断面收缩率:

$$Z = \frac{A_0 - A_u}{A_0} \times 100$$

in:

F_p is the yield load, in N;

F_m is the maximum load, in N;

A_0 is the original cross-sectional area in mm^2 ;

L_0 is the original gauge length , in mm;

L_u is the gauge length after fracture , in mm;

A_u is the minimum cross-sectional area after fracture, in mm^2 .

5 Test equipment

5.1 Universal testing machine

Load range: 0-1000 kN , accuracy $\pm 0.5\%$, in compliance with EN ISO 7500-1:2018 calibration requirements.

Loading speed control: stress rate 0.00025/s to 0.0025/s, or strain rate 0.0001/s to 0.001/s.

5.2 Extensometer

Meets EN ISO 9513:2012 calibration requirements with an accuracy of $\pm 0.5\%$.

Measuring range: covers the elastic and plastic deformation stages of the sample.

5.3 Measurement tools

Vernier caliper: accuracy ± 0.02 mm, used to measure sample size.

Micrometer: accuracy ± 0.001 mm, used to measure cross-sectional area.

5.4 Environmental Control

Temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

6. Sample preparation

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6.1 Specimen type

比例试样：标距长度 L_0 与横截面积 A_0 的平方根成比例，常用 $L_0 = 5.65\sqrt{A_0}$ 。

Non-proportional specimen: The gauge length L_0 is fixed, such as 50 mm or 80 mm.

Specimen shape: round, rectangular, tubular or wire. Specific dimensions refer to EN ISO 377:2017.

6.2 Sample requirements

The surface of the specimen is smooth, without cracks, oxide layer or processing defects.

Surface roughness $R_a < 0.2 \mu\text{m}$ (polished).

The specimens shall be taken in the rolling direction of the material unless otherwise agreed.

6.3 Number of samples

The number of samples in each batch shall not be less than 3 to ensure statistical representativeness.

If the result deviation is large ($>10\%$), the number of samples needs to be increased to 5.

6.4 Sample marking

The test specimens shall be marked with batch number, brand (such as S355JR, 6061-T6) and test items, and the marking shall not affect the test area.

6.5 Sample measurement

Measure the original cross-sectional area of the sample A_0 and gauge length L_0 , accuracy $\pm 0.02 \text{ mm}$.

7 Test steps

7.1 Equipment Calibration

The testing machine was calibrated using a standard force sensor with a load deviation of $\leq \pm 0.5\%$.

The strain measurement was calibrated using a standard extensometer with a deviation of $\leq \pm 0.5\%$.

7.2 Test conditions

Ambient temperature: 10°C to 35°C , $20 \pm 5^\circ\text{C}$ recommended.

Relative humidity: 30%-80%, $50 \pm 10\%$ recommended.

No vibration, no corrosive gas environment.

7.3 Test operation

Install the specimen in the testing machine fixture, ensuring that the specimen axis is aligned with the fixture centerline.

Apply initial load (not exceeding 10% of yield load) and eliminate installation gaps.

Select a loading speed:

Elastic stage: stress rate 0.00025/s to 0.0025/s.

Plastic stage: strain rate 0.0001/s to 0.001/s.

The load-displacement curve was recorded until the specimen broke.

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Each sample was tested once and repeated 3-5 times to ensure the stability of the results.

7.4 Outcome Measurement

Record the yield load F_p and maximum load F_m .

Use an extensometer to measure the strain at the yield stage (e.g. $R_p 0.2$).

After the specimen breaks, measure the post-break gauge length L_u and cross-sectional area A_u .

7.5 Result calculation

屈服强度或 $R_{p0.2}$:

$$R_p = \frac{F_p}{A_0}$$

抗拉强度:

$$R_m = \frac{F_m}{A_0}$$

断后延伸率:

$$A = \frac{L_u - L_0}{L_0} \times 100$$

断面收缩率:

$$Z = \frac{A_0 - A_u}{A_0} \times 100$$

8 Evaluation of test results

8.1 Mechanical properties range

The range of mechanical properties of metal materials depends on the material :

低碳钢 (S355JR) : $R_{p0.2}$ 355 MPa, R_m 470-630 MPa, A 20%-25%。

铝合金 (6061-T6) : $R_{p0.2}$ 240 MPa, R_m 310 MPa, A 8%-12%。

不锈钢 (304) : $R_{p0.2}$ 205 MPa, R_m 520 MPa, A 40%-50%。

8.2 Deviation Assessment

of 3-5 specimens is $< \pm 10\%$, otherwise retesting is required.

If the performance value exceeds the material technical requirements, the reasons need to be analyzed (such as specimen defects, improper loading speed).

8.3 Analysis of influencing factors

Loading speed: Too fast a speed ($> 0.0025/s$) will result in a higher yield strength (deviation $> 5\%$).

Specimen quality: Surface roughness $R_a > 0.2 \mu m$ or defects can lead to premature fracture (deviation $> 10\%$).

Fixture alignment: Misaligned fixtures can cause stress concentration and reduce elongation (deviation $> 15\%$).

Microstructure: Uneven grain size ($> \pm 0.2 \mu m$) or excessive inclusions will reduce performance (deviation $> 10\%$).

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9 Test Report

The test report should include the following:

Sample information: material type, brand, batch number, size, sampling direction.

Test conditions: device model, loading speed, ambient temperature (10°C to 35°C), humidity (30%-80%).

Test results: yield strength ($R_{p0.2}$), tensile strength (R_m), elongation after fracture (A), reduction of area (Z), average value and deviation.

Evaluation conclusion: whether it meets the technical requirements of the material.

Test date and operator's signature.

Appendix A (Informative Appendix) Reference values of mechanical properties of typical metal materials

Material Type	Brand/category	$R_{p0.2}$ (MPa)	R_m (MPa)	A(%)	Z(%)	Typical Applications
Mild Steel	S355JR	355	470-630	20-25	50-60	Building Structure
Aluminum Alloy	6061-T6	240	310	8-12	20-30	Aerospace structures
Stainless steel	304	205	520	40-50	60-70	Food Equipment

Appendix B (Informative Appendix) Recommended table of specimen dimensions

Specimen type	Gauge length L_0 (mm)	Cross-sectional area A_0 (mm ²)	Applicable Materials
Proportional test specimen	$5.65\sqrt{A_0}$	50-200	Steel, aluminum alloy
Non-proportional specimens	50	20-100	Thin plates, wires

Appendix C (Informative Appendix) Test Environment Requirements

Temperature: 10°C to 35°C, 20±5°C recommended.

Humidity: 30%-80%, 50±10% recommended.

No vibration, no corrosive gas environment.

Test bench levelness: deviation <0.02 mm/m.

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Part 3: Performance Optimization of Cemented Carbide

Chapter 7: Mechanical Properties Control of Cemented Carbide

7.0 Mechanical Properties of Cemented Carbide

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7.0.1.2 Factors affecting hardness

7.0.1.3 Microscopic mechanism of hardness

7.0.1.4 Application significance of hardness

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7.0.2.2. Measurement method of fracture toughness of cemented carbide

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7.0.2.5. Application significance of cemented carbide fracture toughness

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7.0.6. Impact resistance of cemented carbide

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- 7.0.6.2. Measurement method of impact resistance of cemented carbide
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 - 7.1.1.1 Grain size effect
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IIoT monitors carburizing temperature in real time (850-950°C, deviation $\pm 1.5^{\circ}\text{C}$) to optimize carburizing layer quality .

 - 7.5.5 The First Year of AI in China's Tungsten Industry
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