Tungsten Cemented Carbide

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

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

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.

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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Chapter 3: Physical and Chemical Properties of Cemented Carbide

Tungsten Cemented Carbide has become the core material for cutting tools, wear-resistant parts, mining equipment, aerospace, chemical equipment, nuclear power facilities and deep-sea devices due to its excellent physical and chemical properties. These properties include mechanical properties (hardness, toughness, compressive strength, flexural strength), thermal properties (thermal conductivity, thermal expansion coefficient, high temperature stability, thermal shock resistance), chemical stability (corrosion resistance, oxidation resistance) and electrical and magnetic properties (conductivity, Co phase magnetism), which are derived from the covalent bond rigidity of tungsten carbide (WC) and the plastic synergy of cobalt (Co) or nickel (Ni) bonding phase.

This chapter analyzes each physicochemical property, inspection and testing methods, factors affecting various aspects of performance, and extended application cases, and deeply explores the theoretical basis, testing technology, regulation mechanism, environmental adaptability, and working condition performance. Through detailed theoretical models, precise experimental data, rich cross-domain cases, and performance impact analysis, this chapter reveals the inherent mechanism of physicochemical properties, providing a comprehensive reference for performance optimization, extreme working condition adaptation, and interdisciplinary research of cemented carbide.

3.1 Mechanical properties of cemented carbide

Mechanical properties are the cornerstone of cemented carbide's reliability in high load, impact, wear and complex stress environments, and are widely used in cutting, mining, stamping, aviation

and deep-sea drilling. This section analyzes hardness, toughness, compressive strength and bending strength one by one, and adds new inspection and testing methods and influencing factors.

3.1.1 Hardness of cemented carbide

Hardness refers to the ability of a material to resist external objects from pressing into or scratching its surface, and is one of the important indicators for measuring the mechanical properties of a material. Hardness generally reflects the strength, wear resistance and deformation resistance of a material, and is often characterized by its ability to resist compression, shear or plastic deformation. Common measurement methods include Brinell hardness (HB), Rockwell hardness (HR), Vickers hardness (HV) and Shore hardness (HS), and their values are calculated based on the type of indenter (such as steel ball or diamond), load size and indentation area (ISO 6507, ASTM E10). For example, the Vickers hardness of cemented carbide is usually HV 1200-2400, depending on the grain size and bonding phase content. Hardness is closely related to the material microstructure (such as grain size, phase composition) and heat treatment, and is a key basis for selecting materials and evaluating durability.

The Vickers hardness (HV) of cemented carbide is 1500 - 2500 ± 30, far exceeding high-speed steel (HV 800 - 1000), ceramics (HV 1200 - 1800) and titanium alloys (HV 300 - 400), which is the core of its wear resistance. The hardness comes from the covalent bond network of WC (WC bond energy 6.0 eV ± 0.2 eV, bond length 2.0 Å ± 0.05 Å), and its hexagonal crystal structure (P6m2, Young's modulus 700 GPa ± 10 GPa) provides resistance to plastic deformation. The hardness of cemented carbide containing 10% Co is HV 1800 ± 30, and that of cemented carbide containing 20% Co drops to HV 1400 ± 30, because the softness of the Co phase (HV 300 - 400, face-centered cubic FCC structure) reduces the compressive strength.

cemented carbide hardness is outstanding.
At 600°C, the hardness of cemented carbide containing 6% Co maintains HV 1500±30, drops to HV 1200±20 at 800°C, and drops to HV 1000±30 at 1000°C, which is better than high-speed steel (dropped to HV 500 at 600°C) and ceramic (dropped to HV 800 at 1000°C). Adding Cr_3C_2 (0.5%1%) increases the hardness to HV 1900 - 2200±50 through solid solution strengthening (Cr atomic radius 1.28 Å , lattice strain <2%±0.2%) . For example, a cemented carbide tool (HV 1900) containing 8% Co and 0.5% Cr_3C_2 has a wear amount of <0.1mm±0.02mm and a life of 15 hours±1 hour in high-speed cutting of stainless steel (tensile strength>1000 MPa, cutting speed 200 m/min, friction coefficient<0.3±0.05), which is better than ceramic tools (life<5 hours, wear amount>0.3mm).

The impact of the environment on hardness requires attention.
In a hot and humid environment (40°C, 90% humidity, 168 hours), micro-corrosion of the Co phase is induced (weight loss <0.1 mg/cm² ± 0.02 mg/cm² , corrosion depth <1μm±0.2μm), and the hardness decreases by <2%±0.5%; in an extremely cold environment (40°C), the hardness increases slightly by 1%±0.3% due to the embrittlement of the Co phase (plastic strain decreases by

<3%±0.3%); in high pressure (>100 MPa, 5000 m deep sea), there is no significant change (decrease <0.5%±0.1%); radiation (nuclear power, 10^4Gy , γ-rays) induces point defects, and the hardness decreases by <1%±0.2%.

Ni-containing cemented carbide (12% Ni, HV 1700±30) is more stable in marine environment (salinity 3.5%, pH 8, Cl^-19 g/L), with a hardness drop of <1%. In practical applications, cemented carbide rollers containing 6% Co have a wear depth of <0.05mm±0.01mm and a lifespan of >300 hours±20 hours in mining (granite, rock hardness>1000 MPa, impact frequency>1000 times/min), which is better than high-speed steel (lifespan<50 hours).

Optimizing hardness requires a trade-off with toughness.
Adding TiC (10%15%, hardness 20 GPa±1 GPa) increases the hardness to HV 2000±50, while reducing the density (to 12 g/cm³ ± 0.1 g/cm³) , which is suitable for lightweight aviation parts, such as turbine blade molds (load>2000 MPa, deformation tolerance<0.01mm). In the composite stamping (600°C, frequency>10^4 times/hour), the surface roughness of the cemented carbide mold containing 15% TiC is Ra<0.1μm±0.02μm, and the life is increased by 40%±5%, which is better than steel molds (Ra>0.5μm, life<2000 hours). Cross-domain comparison shows that the hardness of cemented carbide is better than high-strength steel (HV 600800) and titanium alloy (HV 300400), but inferior to diamond (HV >8000).

3.1.1.1 Hardness expression method

There are many ways to express hardness, suitable for different test scenarios and material comparisons:

Vickers hardness (HV)

Vickers hardness (HV) is a standard method for accurately measuring the hardness of materials. It uses a diamond pyramid indenter (vertex angle 136°) to press into the material surface under a specified load (usually 5-100 kgf , the range can be extended to 1-120 kgf), and after holding for 10-15 seconds, the diagonal length of the indentation (d, unit mm) is measured to calculate the hardness value. The formula is: $HV = 1.8544 \times F / d^2$, where F is the applied load (kgf), d is the average diagonal length of the indentation (mm), and the result is expressed in kgf / mm^2 , which is usually directly marked as the HV value (ISO 6507-1:2018).

Vickers hardness is applicable to a variety of materials, including cemented carbide, steel, ceramics and thin layer materials, because of its small indentation (diameter 0.01-1 mm), high accuracy (error <5%) and wide test range (HV 10-3000+). For example, the HV of conventional cemented carbide is 1200-2000, while that of nano-scale cemented carbide (grains 0.05-0.2 μm) can reach 2000-2400 (Journal of Materials Science 2025). Its advantage is that it can test tiny areas (such as coatings) or thin sheets (thickness>0.1 mm), but the test time is long and the surface flatness requirements are high (Ra<0.8 μm , ITIA 2024).

Rockwell hardness (HRC/HRB)

Rockwell hardness (HRC/HRB) is a common method for measuring the hardness of materials. The indenter (diamond cone or steel ball) is pressed into the material under the initial load (10 kgf) and the total load (60-150 kgf), and the hardness value is determined by measuring the difference in indentation depth (ASTM E18-22). It is characterized by fast testing, small indentation, and simple operation, and is widely used in metal materials.

HRC : Use a diamond cone indenter (vertex angle 120°) with a total load of 150 kgf , suitable for high hardness materials (such as hardened steel, cemented carbide). The HRC value is calculated by the formula: HRC = 100 - (h/0.002), where h is the indentation depth (mm). The HRC range is usually 20-70, for example, cemented carbide HRC 60-70, equivalent to Vickers hardness HV 1200-2400.
HRB : Use a 1/16 inch steel ball indenter with a total load of 100 kgf , suitable for softer materials (such as annealed steel, copper alloys). The HRB value calculation formula is: HRB = 130 - (h/0.002), ranging from 20-100. For example, the HRB value of annealed steel is about 70-90 (ITIA 2024).
The advantage of Rockwell hardness is that it can be read directly with high accuracy (error <3%), but it is not suitable for thin materials or small areas (ISO 6508-1:2016).

Brinell hardness (HB)

Brinell hardness (HB) is a method of measuring the hardness of a material by pressing a hardened steel ball or tungsten carbide ball indenter (usually 2.5, 5 or 10 mm in diameter) into the material surface under a specified load (F, usually 500-3000 kgf), holding it for a certain time (10-30 seconds), and then measuring the indentation diameter (d, in mm) to calculate the hardness. The formula is: $HB = (2F) / (\pi D(D - \sqrt{(D^2 - d^2)}))$, where D is the indenter diameter (mm), F is the load (kgf), d is the indentation diameter (mm), and the result is expressed in kgf / mm ² (ASTM E10-18).

Brinell hardness is suitable for softer or medium hardness materials (such as steel, cast iron, non-ferrous metals), and the range is usually HB 30-650. For example, the HB of unhardened steel is about 120-200, while cemented carbide is usually not suitable for this method due to its high hardness (HV 1200-2400) (ITIA 2024). Its advantage is that the indentation area is large, reflecting the average performance of the material, and it is suitable for non-uniform materials, but not for thin parts or high hardness materials (the error is about 3%-5%, ISO 6506-1:2014).

Mohs hardness
Mohs hardness is a relative scale for qualitatively measuring the hardness of materials. It was proposed by German mineralogist Friedrich Mohs in 1812 to assess hardness by comparing the material's ability to resist scratching. The method uses 10 standard minerals as the benchmark, with

hardness graded from 1 (softest) to 10 (hardest): 1-talc, 2-gypsum, 3-calcite, 4-fluorite, 5-apatite, 6-orthoclase, 7-quartz, 8-topaz, 9-corundum, 10-diamond. During the test, scratch the surface of the material with a standard sample. If a mark can be left, the material's hardness is lower than that of the standard sample.

Mohs hardness is simple and intuitive, and is applicable to minerals and some engineering materials, but it has low accuracy and is only a relative value. For example, the Mohs hardness of cemented carbide is about 9-9.5, close to corundum and much higher than steel (about 5-6) (ITIA 2024). Its limitations are that it cannot quantify the hardness difference (for example, the difference between 9 and 10 is much greater than that between 1 and 2), and it is not suitable for testing inhomogeneous materials or thin layers (the error is about ±0.5).

When converting, please pay attention to the nonlinear relationship, HV≈10·HRC+900 (error <5%), HB and Mohs conversion error>10%. In actual application, HV is the main method, and HRC/HS is the auxiliary method to ensure performance consistency>95%±2%.

3.1.1.2 Hardness test method

Hardness testing ensures measurement accuracy by:

Vickers hardness test (ISO 3878)
The hard alloy containing 10% Co (HV 1800±30) uses a 10 kg load, an indentation diagonal of 2030 μm±0.5 μm , a microscope magnification of 400 times±10 times, and an error of <1%±0.2%. The environment requires 25°C±2°C, humidity <60%±5%, and the sample surface Ra<0.2 μm±0.05 μm . For example, the mold containing 15% TiC (HV 2000±50) passes the Vickers test to ensure a stamping accuracy of <0.01mm.

Rockwell hardness test (ISO 6508)
The hard alloy containing 6% Co (HRC 90±1) adopts HRC scale, preload 10 kg±0.1 kg, main load 150 kg±0.1 kg, hold 5 s±0.5 s, error <2%±0.5%. Suitable for the site, such as the tool containing 8% Co (HRC 89±1).

Portable Hardness Tester (Leeb, ASTM A956)
Cemented carbide containing 12% Co (HS 85±2) uses an impact energy of 11 N·mm±0.5 N·mm with an error of <3%±0.5%. Suitable for mining sites, such as rollers (HS 87±2).

Ultrasonic hardness testing (ASTM A1038)
Cemented carbide containing 8% Co (HV 1900±50) uses ultrasonic contact impedance with a frequency of 20 kHz±0.5 kHz and an error of <2%±0.5%, which is suitable for complex shapes such as aviation molds.

Nanoindentation Testing

The cemented carbide containing 10% Co (hardness 20 GPa±1 GPa) uses a Berkovich indenter with a load of 10 mN±0.1 mN , an indentation depth of <200 nm±10 nm, and an error of <5%±1%, which is suitable for coating detection.

The test requires calibration (standard block error <1%) and avoidance of vibration (acceleration <0.1 m/s²) . For example, a mold containing 15% TiC is tested by Vickers and nanoindentation to ensure a life of >6000 hours ±500 hours.

3.1.1.3 Factors affecting hardness

Composition of cemented carbide

As the Co content increases (6% to 20%), the hardness decreases from HV 2000±50 to HV 1400±30, because the softness of the Co phase (HV 300400) reduces the deformation resistance. Adding TiC (10%15%) increases the hardness to HV 2000±50, and TaC (1%2%) to HV 1900±50, due to solid solution strengthening (lattice strain <2%±0.2%). The hardness of Cr_3C_2 (0.5%1%) reaches HV 2200 ±50, because Cr atoms inhibit grain boundary sliding (friction coefficient decreases to <0.2±0.05) .

Process of cemented carbide

Sintering temperature (14001500°C±10°C) affects the density of WC phase (>99%±0.1%), and too high temperature (>1550°C) causes volatilization of Co phase (loss <5%±1%), and hardness decreases by 3%5%±1%. Hot isostatic pressing (HIP, 100 MPa±5 MPa) eliminates pores (porosity <0.1%±0.02%) and hardness increases by 2%±0.5%.

Surroundings

High temperature (600 - 1000°C) reduces the WC bond energy (bond length increases by 0.1 Å ± 0.02 Å), and the hardness decreases by 10%30%±2%. Moisture heat (40°C, 90% humidity) causes Co corrosion (weight loss <0.1 mg/cm²) , and the hardness decreases by <2%±0.5%. Extreme cold (40°C) causes Co embrittlement, and the hardness increases by 1%±0.3%. Radiation (10^4 Gy) causes defects, and the hardness decreases by <1%±0.2%.

Surface condition of cemented carbide

Surface roughness (Ra>0.4 μm) reduces indentation accuracy (error>2%±0.5%); coating (such as Al_2O_3 , 5 μm ±1 μm) increases surface hardness to HV 2200±50 due to compressive stress (>500 MPa±50 MPa).

For example, a tool containing 8% Co and 0.5% Cr_3C_2 (HV 1900±50, HIP process) maintains a hardness of HV 1850±30 and a life of >15 hours±1 hour in wet hot cutting (40°C, 90% humidity). Optimization requires low Co (6%8%) and high density process.

3.1.2 Toughness of cemented carbide

The toughness of cemented carbide refers to its ability to resist crack propagation and fracture, and

is a key performance indicator for measuring the impact resistance and reliability of materials. Since cemented carbide uses tungsten carbide (WC) as the hard phase and cobalt (Co) or nickel (Ni) as the bonding phase, its toughness is mainly affected by grain size, bonding phase content, microstructure and preparation process.

Definition of Fracture Toughness

Fracture toughness (KIC) is the ability of cemented carbide to resist crack propagation, usually expressed in MPa·m $^{1/2}$, reflecting the material's fracture resistance when subjected to stress intensity factor at the crack tip (ASTM E399).

Fracture toughness range

Conventional cemented carbide (grain size 1-5 μm) has a KIC of 8-15 MPa·m $^{1/2}$, depending on the Co content. Fine-grained (0.5-1 μm) and ultrafine-grained (0.2-0.5 μm) cemented carbide has a KIC of 7-12 MPa·m $^{1/2}$, and the crack propagation path is more complicated due to the increased grain boundary area (Journal of the Chinese Society of Nonferrous Metals 2024). Nano-scale cemented carbide (0.05-0.2 μm) has a KIC of 6-9 MPa·m $^{1/2}$, with lower toughness and stress concentration due to fine grains (ITIA 2024).

Factors affecting fracture toughness

Binder phase content

When the Co content increases from 6% to 15%, KIC can be increased by 20%-30% (from 8 MPa·m $^{1/2}$ to 10-12 MPa·m $^{1/2}$) because Co provides plastic buffer.

Grain size

the grain size is reduced from 5 μm to 0.2 μm , KIC decreases by about 15%-20%, but the wear resistance is improved.

Microscopic defects

Porosity or cracks reduce KIC by 5%-10%.

Fracture toughness application

Fracture toughness is a key indicator for evaluating the chipping resistance of tools and the impact resistance of molds. For example, in high-speed cutting (200 m/min), the life of cemented carbide with KIC>10 MPa·m $^{1/2}$ can reach 2-3 hours (Journal of Materials Science 2025).

Definition of Impact Toughness

cm² through Charpy or Izod impact test (ASTM E23).

Fracture toughness range:

coarse-grained cemented carbide (>5 μm) is 10-20 J/cm² due to its large grain size and uniform Co distribution.

fine-grained and ultrafine- grained cemented carbides is 5-12 J/cm² , and the toughness decreases as the grain size decreases.

The impact toughness of nano-grade cemented carbide is less than 5 J/cm² , and its impact resistance

is relatively weak.

Factors affecting fracture toughness:

Co content: When Co increases from 6% to 12%, the impact toughness increases by about 30%-40% because the Co phase enhances energy absorption.

Sintering process: Hot isostatic pressing (HIP) reduces porosity and improves impact toughness by 10%-15%.

Ambient temperature: At low temperatures (-50°C), the impact toughness decreases by about 20%-25%, and materials with high Co content are more stable.

Application: Impact toughness is suitable for mining drill bits and stamping dies. Under high-frequency impact (>2000 times/minute), the material life of toughness>10 J/cm² can reach 200-300 hours.

Definition of Fatigue Toughness

Fatigue toughness describes the ability of cemented carbide to resist crack growth under cyclic loading and is usually characterized by fatigue crack growth rate (da/ dN , m/cycle) or fatigue limit (MPa) (ASTM E647).

Fatigue toughness range:

The fatigue limit of conventional cemented carbide is 800-1200 MPa, and the fatigue crack growth rate is about 10^{-6} -10^{-5} m/cycle.

Due to the concentration of grain boundary stress, the fatigue limit of nano-scale cemented carbide is reduced to 600-900 MPa, and the expansion rate is increased to 10^{-5} -10^{-4} m/cycle.

Factors affecting fatigue toughness:

Surface quality: surface roughness Ra>0.8 μm , fatigue life decreases by 20%-30%.

Defects: Porosity or amorphous phase reduces the fatigue limit by 10%-15%.

Coating: PVD TiAlN coating can increase fatigue life by about 15%-20% due to reducing surface crack initiation.

Fatigue toughness application

Fatigue toughness is critical for cyclically loaded tools (such as milling cutters), where fatigue life can reach 1000-1500 hours at 10^7 cycles (500 MPa) .

Definition of Thermal Toughness

Hot toughness reflects the crack resistance of cemented carbide under high temperature thermal cycles or thermal shocks, and is usually characterized by thermal fatigue life (number of cycles) or high temperature fracture toughness (KIC, 1000°C) (ASTM E1830).

Thermal Toughness Range

The thermal fatigue life of conventional cemented carbide is 500-1000 times (500°C), and the high temperature KIC is 6-10 $MPa \cdot m^{1/2}$.

containing TaC or TiC can reach 1000-1500 times, and the high temperature KIC is 7-12 MPa·m $^{1/2}$.

Factors affecting thermal toughness

Thermal expansion mismatch: The mismatch between WC (5.2×10^{-6} /K) and Co (12×10^{-6} /K) leads to thermal stress and a 10%-15% decrease in toughness.

High temperature oxidation: 1000°C oxidation weight gain> 0.1 mg/cm², thermal toughness decreased by about 20%.

Grain size: Nanoscale materials have concentrated thermal stress and their thermal toughness decreases by about 15%-20%.

Application of Thermal Toughness

Thermal toughness is suitable for high temperature cutting (such as aircraft engine parts, 250 m/min), and the service life can reach 2-3 hours.

5. Key factors affecting resilience

Bonding phase composition: Ni or Co-Cr alloy replaces pure Co, and the toughness is improved by 5%-10% because the Ni phase has strong corrosion resistance (corrosion rate <0.03 mm/year, ASTM G31).

Microstructure: η phase or free carbon reduces toughness by 5%-15%, and hot isostatic pressing (HIP) can restore about 10% of the toughness.

Process optimization: Adding grain inhibitors (such as VC 0.2%-0.5%) can increase toughness by 5%-8% (ITIA 2024).

The fracture toughness (K_{1c}) of cemented carbide is 820 MPa·m$^{1/2}$ ± 0.5 , which is better than ceramics (K_{1c} 35 MPa·m$^{1/2}$) and silicon nitride (K_{1c} 68 MPa·m$^{1/2}$) , and slightly lower than high-strength steel (K_{1c} 2030 MPa ·m$^{1/2}$) , supporting high impact conditions such as rock drilling and punching. The toughness originates from the plastic deformation of the Co phase (strain <5%±0.5%, yield strength>500 MPa±20 MPa), dissipating energy through crack deflection (angle>30°±5°) and bridging (bridging force>10 MPa±2 MPa). The K_1 c of cemented carbide containing 12% Co is 15 MPa·m $^{1/2}$ ± 0.3, and that of cemented carbide containing 6% Co is 10 MPa·m $^{1/2}$ ± 0.2.

Co content regulates toughness. When Co increases from 6% to 20%, K_{1c} increases from 8 to 18 MPa·m $^{1/2}$ ± 0.5, due to the enhanced energy absorption (dissipated energy>50 J/m ² ± 5 J/m ²) of the Co phase network (thickness 1030 nm±2 nm, refer to Chapter 2) . Adding TaC (1%2%) increases the grain boundary strength (>50 MPa±5 MPa), K_{1c} increases to 14 MPa·m $^{1/2}$ ± 0.5, and the crack extension depth is <10μm±2μm.

The carbide drill containing 12% Co and 1% TaC has a crack length of <5μm±1μm and a life of >250h±20h in granite drilling (impact frequency>2000 times/min, load>3000 MPa, impact energy>100 J±10 J), which is better than that of ceramic drill (life <50h, crack >20μm).

and humid environment (40°C, 90% humidity, 168 hours), due to Co phase corrosion (depth <2μm±0.5μm, weight loss <0.2 mg/cm² ± 0.05 mg/cm²), K_{1c} decreases by 5 % 10 % ±1%. In extreme cold (40°C), due to Co embrittlement (toughness-strength conversion, strain drop <3%±0.3%), K_{1c} decreases by 3%±0.5%. High pressure (>100 MPa, deep sea) enhances grain boundary bonding, K_{1c} increases by 2 % ± 0.3%. Radiation (10^4Gy) induces Co phase defects (vacancy density < 10^{15} /cm³) , and K_{1c} decreases by <2%±0.3%.

Ni-containing cemented carbide (12% Ni, K_{1c} 13 MPa ·m$^{1/2}$ ± 0.3) is more stable in marine environment (salinity 3.5%, O_2 8 mg/L), with a K_{1c} drop of <2%. For example, Ni-containing rock drilling tools operate in a hot and humid mine (pH 6, humidity 90%, temperature 40°C), with a K_{1c} of 12 MPa·m$^{1/2}$ ± 0.3 , and a life increase of 30%±5%, which is better than Co-containing materials (life reduction of 10%±2%).

Optimizing toughness requires balancing hardness. High Co (>15%) increases K_{1c} to 18 MPa·m$^{1/2}$ ± 0.5 , but the hardness drops to HV 1400±30; adding NbC (0.5%1%) increases K_{1c} to 15 MPa·m$^{1/2}$ ± 0.5 by refining the crack path (crack width <1μm±0.2μm) , and the hardness remains at HV 1800±30.

For example, in high-frequency stamping (>10^4 times/hour, load>2000 MPa), cemented carbide dies with 10% Co and 0.5% NbC have deformation <0.01mm±0.002mm, crack rate <0.5%, and life>6000 hours±500 hours, which is better than steel dies (deformation>0.05mm, life<2000 hours). Cross-domain comparisons show that cemented carbide has better toughness than ceramics and alumina (K_{1c} < 5 MPa ·m$^{1/2}$) , but is inferior to tough steel in high impact toughness (K_{1c} >50 MPa·m$^{1/2}$) .

3.1.2.1 Toughness test method

Toughness testing ensures crack resistance, methods include:

Single Edge Notched Beam (SENB, ASTM E399)
Cemented carbide containing 12% Co (K_{1c} 15 MPa·m$^{1/2}$ ± 0.3) adopts three-point bending, specimen 4×4×20 mm±0.1 mm, notch depth 2 mm±0.05 mm, span 20 mm±0.1 mm, load rate 0.1 mm/min±0.01 mm/min, error <2%±0.5%. Environmental requirements are 25°C±2°C, humidity <60%±5%.

Chevron notch test (ASTM E1304): Cemented carbide containing 6% Co (K_{1c} 10 MPa ·m$^{1/2}$ ± 0.2) uses a V-notch, specimen 5×5×25 mm±0.1 mm, load rate 0.05 mm/min±0.005 mm/min, error <3%±0.5%, suitable for small specimens.

Impact toughness test (ISO 148)
The hard alloy containing 15% Co (impact energy>20 J±2 J) was impacted by Charpy, with a specimen of 10×10× 55 mm±0.1 mm, a pendulum energy of 300 J±5 J, and an error of <5%±1%,

which is suitable for mining tool testing.

Fracture mechanics simulation: Finite element analysis (ANSYS, mesh size <0.1 mm, crack extension error <0.05 mm) was used for cemented carbide containing 10% Co to predict K_{1c} (error <5%±1%), which is suitable for complex stress analysis.

Micro crack analysis

containing TaC (crack depth <10μm±2μm) was evaluated using scanning electron microscopy (SEM, resolution <5 nm±1 nm) (error <5%±1%).

For example, a drill containing 12% Co and 1% TaC passes the SENB test (K_{1c} 14 MPa $\cdot m^{1/2} \pm 0.5$), ensuring an impact life of >250h±20h and a SEM-verified crack length of <5μm±1μm.

3.1.2.2 Overview of factors affecting toughness

Resilience is affected by:

Element

Increasing the Co content from 6% to 20% increases K_{1c} from 8 to 18 MPa$\cdot m^{1/2} \pm 0.5$ due to the plasticity of the Co phase (shear modulus 80 GPa±5 GPa) which enhances crack dissipation (energy>50 J/$m^2 \pm 5$ J/m^2). Ni substitution for Co (12% Ni, K_{1c} 13 MPa $\cdot m^{1/2} \pm 0.3$) reduces toughness due to the low plasticity of Ni (strain <4%±0.5%). Adding TaC (1%2%) increases K_{1c} to 14 MPa$\cdot m^{1/2} \pm 0.5$ due to grain boundary strengthening (bonding strength>50 MPa±5 MPa).

Technology

Sintering time (24 h±0.1 h, 1450°C±10°C) increases the uniformity of Co phase (distribution error <5%±1%) and K_{1c} increases by 5%±1%. Too high temperature (>1550°C) causes Co volatilization and K_{1c} decreases by 3%5%±1%. HIP (100 MPa±5 MPa) reduces defects (porosity <0.1%±0.02%) and K_{1c} increases by 3%±0.5%.

Environment

In case of damp heat (40°C, 90% humidity) , K_{1c} decreases by 5%10%±1% due to Co corrosion (weight loss <0.2 mg/cm^2) ; in case of extreme cold (40°C), K_{1c} decreases by 3%±0.5% due to Co embrittlement; in case of high pressure (>100 MPa), K_{1c} increases by 2%±0.3% due to enhanced bonding; in case of radiation (10^4Gy) , K_{1c} decreases by <2%±0.3% due to defects.

Stress state

When the impact frequency (>2000 times/min) induces fatigue cracks (length >5μm±1μm), K_{1c} decreases by 5%±1%; under static load (<3000 MPa) , K_{1c} is stable .

a drill bit containing 12% Co and HIP process (K_{1c} 15 MPa$\cdot m^{1/2} \pm 0.3$) is operated in a hot and humid mine (40°C, 90% humidity), K_{1c} is maintained at 14 MPa $\cdot m^{1/2} \pm 0.3$, and the life is >250 hours ± 20 hours. Optimization requires high Co (12%15%) and TaC addition.

3.1.3 Strength of cemented carbide

The strength of cemented carbide refers to its ability to resist deformation or fracture due to external forces, and is an important indicator for measuring the material's load-bearing capacity and durability. Since cemented carbide uses tungsten carbide (WC) as the hard phase and cobalt (Co) or nickel (Ni) as the bonding phase, its strength is affected by grain size, bonding phase content, and microstructure. The following are the main types of cemented carbide strength and their detailed descriptions.

3.1.3.1 Transverse Rupture Strength (TRS)

Definition

Bending strength is the ability of cemented carbide to resist fracture in a three-point or four-point bending test. It is measured in mpa and reflects the material's bearing capacity under complex stress.

Scope

conventional cemented carbide (grain size 1-5 μm) is 1800-2500 MPa, and the Co content is 6%-15%.

fine-grained (0.5-1 μm) and ultrafine-grained (0.2-0.5 μm) cemented carbide is 1700-2200 MPa.

nano-sized cemented carbide (0.05-0.2 μm) is 1600-1900 MPa, but the strength is reduced due to the stress concentration at the grain boundaries.

Performance characteristics

The flexural strength is usually 4000-4500 MPa±100 MPa, which is better than high-strength steel (~1500 MPa), ceramics (~1000 MPa) and titanium alloys (~800 MPa), and is suitable for complex stress conditions such as stamping and aviation processing. The Co phase inhibits crack propagation (crack velocity $<10^{-5}$ m/s±10^{-6} m/s) through plastic deformation (strain <5%±0.5%, shear stress <100 MPa±10 MPa). For example, the flexural strength of cemented carbide containing 10% Co is 4200 MPa±100 MPa, and that of cemented carbide containing 15% Co drops to 4000 MPa±100 MPa.

Application

of cemented carbide dies containing 8% Co in automotive steel plate stamping (load>2000 MPa, frequency>10^4times / hour, plate thickness 2 mm±0.1 mm) is <0.5%, and the service life is >6000 hours±500 hours, which is better than that of steel dies (fracture rate>5%, service life <2000 hours).

containing 10% Co and 1% TaC has a fracture rate of <1% and a life of >12 hours ± 1 hour in the cutting of aviation titanium alloy (stress > 2000 MPa, cutting speed 150 m/min), which is better than ceramic tools (life < 4 hours).

Influencing factors

Co content

Increasing from 6% to 15%, the strength drops from 4500 to 4000 MPa±100 MPa because the Co

phase reduces the rigidity; adding NbC (0.5%-1%) increases it to 4600 MPa±100 MPa through solid solution strengthening (grain boundary strength>50 MPa±5 MPa).

Technology

The sintering temperature (1450°C±10°C) ensures WC-Co bonding (bonding strength>50 MPa±5 MPa), and the strength increases by 3%±0.5%; HIP (100 MPa±5 MPa) eliminates cracks (<5 μm±1 μm), and the strength increases by 5%±1%; the cooling rate (>10°C/min) induces stress (>100 MPa±10 MPa), and the strength decreases by 2%±0.3%.

Environment

High temperature (800°C) due to Co softening (yield strength decreased by <400 MPa±20 MPa), decreased to 3800 MPa±100 MPa (decreased by <10%); wet heat (40°C, 90% humidity, 168 hours) due to Co corrosion (weight loss <0.1 mg/cm² ± 0.02 mg/cm²) , decreased by 5%±1%; high pressure (>100 MPa) increased by 2%±0.3%; extreme cold (-40°C) increased by 3%±0.5%; radiation (10^4 Gy) decreased by <1%±0.2%. Containing Cr (0.5%-1%) forms a Cr_2O_3 protective layer (thickness <5 nm±1 nm), wet heat decreased by <2%.

Sample geometry

Thickness > 4 mm ± 0.1 mm reduces stress concentration (coefficient < 1.2 ± 0.1), and strength increases by 2% ± 0.3%; surface defects (Ra > 0.4 μm) induce cracks, reducing strength by 3% ± 0.5%.

Detection Methods

Three-point bending (ISO 3327)

Specimen 4×4×40 mm±0.1 mm, span 20 mm±0.1 mm, load rate 0.2 mm/min±0.02 mm/min, error <2%±0.5%, environment 25°C±2°C.

Four-point bend (ASTM C1161)

The specimen is 3×4×45 mm±0.1 mm, the load point spacing is 10 mm±0.1 mm, and the error is <3%±0.5%, which is suitable for uniform stress analysis.

Ultrasonic testing (ASTM E588)

Longitudinal wave (frequency 5 MHz±0.1 MHz, wave velocity 6 km/s±0.1 km/s), detect cracks (<5 μm±1 μm), error <5%±1%.

Digital Image Correlation (DIC)

Strain error <0.1%±0.02%, high-resolution camera (resolution <5 μm±1 μm), fracture strain analysis, error <5%±1%.

3.1.3.2 Compressive Strength

Definition: Compressive strength is the ability of cemented carbide to resist compression deformation or damage, measured in MPa, and reflects the material's bearing capacity under high loads.

Scope

The compressive strength of cemented carbide is usually 4000-6000 mpa±100 mpa, which is much higher than high-strength steel (~2000 mpa), ceramics (~3000 mpa) and titanium alloy (~1000 mpa), and is suitable for high-load conditions such as deep-sea drilling and extrusion.
Nanoscale materials can reach 5000-6500 mpa ± 100 mpa, which is enhanced by grain refinement.

Performance characteristics

The compressive strength is dominated by the rigidity of wc (poisson's ratio 0.2±0.02, young's modulus 700 gpa±10 gpa), and the co phase relieves stress concentration (stress decay >20%±2%, shear stress <100 mpa±10 mpa). For example, the compressive strength of cemented carbide containing 10% co is 4500 mpa±100 mpa, and that containing 6% co reaches 4700 mpa±100 mpa.

Application

The carbide drill bit containing 6% Co has a deformation of <0.005 mm±0.001 mm and a life of >300 hours±20 hours in hard rock drilling (stress>3000 MPa, rock hardness>1000 MPa, drilling speed>10 m/h±1 m/h), which is better than that of steel drill bits (deformation>0.05 mm, life<100 hours).

The deformation of the cemented carbide roller containing Cr (0.5%-1%) during ore crushing (load > 4000 MPa, particle size < 10 mm ± 2 mm) is < 0.003 mm ± 0.001 mm, and the service life is increased by 35% ± 5%.
The extrusion die containing 8% Co has a deformation of <0.01 mm±0.002 mm and a life of >5000 hours±500 hours in aluminum alloy processing (600°C, load>4000 MPa, extrusion speed>5 m/min±0.5 m/min), which is better than that of steel die (life<1000 hours).

Influencing factors

Element

When the Co content increases from 6% to 20%, the strength decreases from 4700 to 4100 MPa±100 MPa because the Co phase reduces the rigidity (Young's modulus 200 GPa±10 GPa); Cr (0.5%-1%) increases to 4800 MPa±100 MPa because the CrCo solid solution is enhanced (bonding strength >60 MPa±5 MPa); TiC (10%-15%) decreases to 4300 MPa±100 MPa because the density decreases (<13 g/cm^3 ± 0.1 g/cm^3) .

Technology

Sintering pressure (510 MPa±0.5 MPa) improves density (>99%±0.1%) and strength increases by 3%±0.5%; HIP (100 MPa±5 MPa) eliminates pores (porosity <0.1%±0.02%) and increases strength by 5%±1%; excessively high temperature (>1550°C) causes WC decomposition (carbon loss <1%±0.2%) and decreases strength by 3%±0.5%.

Environment

High temperature (800°C) decreased to 4000 MPa±100 MPa (decreased by <10%) due to reduced bond energy (bond length increased by 0.1 Å ± 0.02 Å); damp heat (40°C, 90% humidity, 168 hours) decreased by 3%±0.5% due to Co micro-corrosion (weight loss <0.1 mg/ cm^2 ± 0.02 mg/cm^2) ; extreme cold (-40°C) increased by 2%±0.3% due to enhanced WC rigidity; high pressure (>100 MPa, deep sea) increased by 3%±0.5%; radiation (10^4 Gy) decreased by <1%±0.2%. Ni-containing

(12% Ni, 4500 MPa±100 MPa) is more stable in marine environment (salinity 3.5%, pressure 50 MPa), with a decrease of <1%.

Loading rate

High rate (>1 mm/min) induces microcracks (length <5 μm±1 μm), with a reduction of 2%±0.3%; low rate (<0.5 mm/min) keeps the strength stable.

Detection Methods

Cylindrical specimen compression (ASTM C773)

The specimen diameter is 10 mm±0.1 mm, the height is 20 mm±0.1 mm, the compression rate is 0.5 mm/min±0.05 mm/min, the error is <2%±0.5%, the environment is 25°C±2°C, and the surface Ra is <0.2 μm±0.05 μm .

Static load test

A servo hydraulic press (load accuracy ±1 kN , maximum load 5000 kN ±10 kN) is used with an error of <3% ±0.5%, which is suitable for large specimens.

Non-destructive testing (ultrasonic, ASTM E494)

Longitudinal wave flaw detection (wave speed 6 km/s±0.1 km/s, frequency 5 MHz±0.1 MHz), error <5%±1%, suitable for on-site detection.

Finite element simulation

ANSYS (mesh size <0.1 mm, stress error <10 MPa) was used to predict the strength with an error of <5% ± 1%.

3.1.3.3 Tensile Strength

Definition

Tensile strength is the ability of cemented carbide to resist tensile fracture and is measured in mpa, but is usually low due to its brittleness.

Scope

The tensile strength of conventional cemented carbide is 800-1200 mpa, which is limited by grain boundary weakening.

nano -scale materials can reach 1000-1400 MPa, and trace amounts of Ni improve toughness.

Influencing factors

An increase in Co content (e.g., 6% to 15%) improves the product by about 10%-15%; defects (e.g., pores) decrease by about 5%-10%.

application

Suitable for parts with small tensile loads, such as wire drawing dies and micro-drawing parts.

3.1.3.4 Fatigue Strength

Definition

Fatigue strength is the ability of cemented carbide to resist fatigue fracture under cyclic load, measured in mpa.

Scope

The fatigue limit of conventional cemented carbide is 800-1200 MPa, 10^7 cycles .

nanoscale materials is reduced to 600-900 MPa due to the concentration of grain boundary stress.

Influencing factors

Surface roughness Ra>0.8 μm reduces fatigue life by 20%-30%; coating (such as TiAlN) increases it by about 15%-20%.

Application

Suitable for cyclically loaded tools, such as milling cutters, with a lifespan of 1000-1500 hours.

3.1.3.5 Summary of influencing factors

Bonding phase

As the Co content increases, the strength increases, but too high a Co content (>15%) may reduce the hardness.

Grain size

Refining the grain size (e.g. 0.2 μm) increases compressive strength but reduces bending and fatigue strength.

Defect

Porosity, amorphous phase or cracks reduce all strength types by 5%-15%.

3.1.3.6 Environment and Optimization Suggestions

Environmental impact

High temperature (800°C) reduces strength by 10%±1%; damp heat (40°C, 90% humidity) reduces strength by 3%-5%; high pressure (>100 MPa) increases strength by 2%-3%; extreme cold (-40°C) increases strength by 2%-3%; radiation (10^4 Gy) affects strength by <1%. Cemented carbides containing Ni or Cr are more stable in harsh environments (such as ocean, damp heat).

Optimization suggestions

Adopt low Co (6%-8%), high density (>99%±0.1%) and HIP process, add NbC or TaC to enhance strength and extend life by 30%-35%.

3.2 Thermal properties of cemented carbide

Thermal properties determine how cemented carbide performs in high temperature cutting, thermal cycles and extreme thermal environments, and are widely used in aero engines, gas turbines and nuclear power. This section analyzes thermal conductivity, thermal expansion coefficient, high temperature stability and thermal shock resistance.

3.2.1 Thermal conductivity of cemented carbide

The thermal conductivity of cemented carbide is 80120 W/m·K±5 W/ m·K , which is higher than

ceramics (2030 W/ m·K), alumina (30 W/ m·K), and lower than copper (400 W/ m·K) and graphite (150 W/ m·K). It is determined by WC (110 W/m·K±5 W/ m·K , dominated by electronic thermal conductivity) and Co (70 W/m·K±5 W/ m·K , phonon scattering>20%±2%). The thermal conductivity of cemented carbide containing 10% Co is 100 W/m·K±5 W/ m·K , and that containing 15% Co drops to 90 W/m·K±5 W/ m·K .

High thermal conductivity reduces tool temperature. In high-speed cutting of aviation aluminum alloy (200 m/min, heat flux density >10 MW/m² ± 1 MW/m²), the surface temperature of cemented carbide tools containing 8% Co is < 700 ° C±20°C, the wear amount is <0.1mm±0.02mm, and the life is >12 hours±1 hour, which is better than ceramic tools (temperature >900°C, life <4 hours). Adding TiC (15%, thermal conductivity 30 W/m·K±5 W/ m·K) reduces it to 85 W/m·K±5 W/ m·K , but improves high temperature stability, suitable for aviation nozzles (1100°C, gas flow rate >500 m/s±50 m/s). For example, the nozzle containing 15% TiC in the gas turbine has a thermal diffusivity of >30 mm² / s ± 2 mm² / s, a deformation of <0.01mm±0.002mm, and a life of >6000 hours±500 hours.

Environmental impacts require attention. At high temperature (800°C), the thermal conductivity drops to 90 W/m·K±5 W/ m·K (a decrease of <10%) due to Co phase electron scattering (mobility decreases <10 ⁴ cm ² /V·s±10 ³ cm ² /V·s) ; at humid heat (40°C, 90% humidity, 168 hours), the thermal conductivity drops to <2%±0.5% due to surface oxidation (oxidation layer <1μm±0.2μm); at extreme cold (40°C), the thermal conductivity increases by 1%±0.3% due to enhanced phonon thermal conductivity; at high pressure (>100 MPa), the thermal conductivity increases by 2%±0.3%; at radiation (10 ⁴ Gy), the thermal conductivity drops by <1%±0.2%. Ni-containing cemented carbide (12% Ni, 95 W/m·K±5 W/ m·K) is more stable in marine environments (salinity 3.5%, pressure 50 MPa), with a decrease of <1%.

For example, the thermal conductivity of the Ni-containing mold was maintained at 93 W/m·K±5 W/ m·K and the deformation was <0.01mm±0.002mm during wet hot stamping (40°C, 90% humidity, 600°C), which was better than that of the Co-containing material (decrease >3%±0.5%).

Thermal conductivity optimization requires balancing high temperature performance. In thermal cycle cutting (25800°C, 1000 times, temperature difference >500°C±10°C), the crack length of cemented carbide tools containing 10% Co is <5μm±1μm, which is better than ceramics (crack >20μm). Cross-domain comparison shows that the thermal conductivity of cemented carbide is better than that of ceramics and titanium alloys (20 W/ m·K), but inferior to copper and graphite.

3.2.1.1 Thermal conductivity test method

Thermal conductivity testing methods include:
Laser Flash Method (ASTM E1461)
cemented carbide containing 10% Co (100 W/m·K±5 W/ m·K), the sample diameter is 12.7 mm±0.1 mm, the thickness is 2 mm±0.1 mm, the laser pulse width is 0.5 ms±0.05 ms , the thermal

diffusivity error is <1%±0.2%, and the total error is <2%±0.5%. The environment requires 25°C±2°C.

Steady-state heat flow method (ASTM C177)

Cemented carbide containing 8% Co (98 W/m·K±5 W/ m·K) uses a specimen of 50×50× 10 mm±0.1 mm, a temperature difference of 10°C±0.5°C, a heat flow accuracy of ±0.1 W/m² , and an error of <3%±0.5%.

Transient hot wire method (ASTM D5930): Cemented carbide containing TiC (85 W/m·K±5 W/ m·K) uses a hot wire power of 0.1 W±0.01 W, a temperature resolution of 0.1°C±0.05°C, an error of <5%±1%, and is suitable for non-uniform materials.

Infrared temperature measurement simulation

The heat flux distribution of cemented carbide containing 10% Co (thermal conductivity error <5%±1%) was analyzed using an infrared camera (resolution <0.1°C±0.05°C) (error <5%±1%).

For example, a tool containing 10% Co is tested by the laser flash method (100 W/m·K±5 W/ m·K), and the infrared verification surface temperature is <700°C±20°C, ensuring a cutting life of >12 hours±1 hour.

3.2.1.2 Factors affecting thermal conductivity

Thermal conductivity is affected by:

Composition: When the Co content increases from 10% to 15%, the thermal conductivity decreases from 100 to 90 W/m·K±5 W/ m·K due to the enhanced phonon scattering of Co (scattering rate>20%±2%). TiC (15%) decreases to 85 W/m·K±5 W/ m·K due to low thermal conductivity (30 W/ m·K). Ni (12%) increases to 95 W/m·K±5 W/ m·K due to higher electronic thermal conductivity (mobility>1.5×10 ⁴ cm ² /V·s±10 ³ cm ² /V·s).

Process: Sintering temperature (1450°C±10°C) improves WC phase continuity (contact area>90%±2%), and thermal conductivity increases by 3%±0.5%; HIP (100 MPa±5 MPa) reduces porosity (<0.1%±0.02%), and increases by 2%±0.3%. Too high temperature (>1550°C) causes Co segregation (segregation rate<5%±1%), and decreases by 3%±0.5%.

Environment: High temperature (800°C) decreases by 10%±1% due to electron scattering; damp heat (40°C, 90% humidity) decreases by <2%±0.5% due to the oxide layer (<1μm±0.2μm); extreme cold (40°C) increases by 1%±0.3% due to phonon thermal conduction; high pressure (>100 MPa) increases by 2%±0.3%; radiation (10 ⁴ Gy) decreases by <1%±0.2%.

Sample size: Thickness (>2 mm±0.1 mm) reduces boundary scattering (<10%±2%) and increases thermal conductivity by 2%±0.3%; surface roughness (Ra>0.4 μm) causes heat dissipation loss, which decreases by 1%±0.2%.

For example, a tool containing 8% Co and HIP process (100 W/m·K±5 W/ m·K) maintains a thermal conductivity of 95 W/m·K±5 W/ m·K in high temperature cutting (800°C) and a life of >12 hours±1 hour. Optimization requires low TiC and HIP.

3.2.2 Thermal expansion coefficient

The coefficient of thermal expansion (CTE) of cemented carbide is 46×10^{-6} /K±0.1×10^{-6} /K, which is lower than that of ceramics (810×10^{-6} /K), high-strength steel (12×10^{-6} /K) and titanium alloy (9×10^{-6} /K), and is determined by the weighted average of WC (4.5×10^{-6} /K±0.1×10^{-6} /K) and Co (12×10^{-6} /K±0.1×10^{-6} /K). The CTE of cemented carbide containing 10% Co is 5.5×10^{-6} /K±0.1×10^{-6} /K, and that containing 15% Co increases to 5.8×10^{-6} /K±0.1×10^{-6} /K.

Low CTE reduces thermal stress (<200 MPa±20 MPa). In high temperature stamping (600°C, load>2000 MPa, temperature difference>400°C±10°C), the deformation of cemented carbide molds containing 8% Co is <0.005mm±0.001mm, and the accuracy is improved by 5 times, which is better than steel molds (deformation>0.05mm, accuracy error>0.1mm). Adding TiC (15%, CTE 7×10^{-6} /K±0.1×10^{-6} /K) is reduced to 5.0×10^{-6} /K±0.1×10^{-6} /K, and the thermal crack length is <1μm±0.2μm.

For example, the deformation tolerance of TiC -containing nozzles in aviation composite forming (800°C, pressure >100 MPa) is <0.01mm±0.002mm, and the life is >5000 hours±500 hours, which is better than ceramic nozzles (cracks >10μm).

The environmental impact is limited. High temperature (1000°C) increases CTE by 0.2×10^{-6} /K±0.05×10^{-6} /K due to lattice expansion (lattice constant increases by 0.1%±0.02%); damp heat (40°C, 90% humidity, 168 hours) has no obvious change (error <0.05×10^{-6} /K); high pressure (>100 MPa) decreases by 0.1×10^{-6} /K±0.02×10^{-6} /K; extreme cold (40°C) decreases by 0.1×10^{-6} /K±0.02×10^{-6} /K; radiation (10^{4} Gy) increases by <0.05×10^{-6} /K±0.01×10^{-6} /K. Ni-containing cemented carbide (12% Ni, 5.2×10^{-6} /K±0.1×10^{-6} /K) is more stable in the marine environment (salinity 3.5%, pressure 50 MPa).

For example, a Ni-containing pipeline operated in deep-sea oil and gas (pH 8, 5000 m depth) for 3 years, with a CTE of 5.3×10^{-6} /K±0.1×10^{-6} /K and a deformation of <0.01mm±0.002mm.

CTE optimization requires low Co (6% 8%) and TiC addition. The crack length of the tool containing 10% Co in thermal cycles (25800°C, 1000 times, temperature difference >500°C±10°C) is <5μm±1μm, which is better than ceramics (crack >20μm). Cross-field comparison shows that cemented carbide CTE is better than steel and titanium alloy, but inferior to Invar alloy in ultra-low expansion (<2×10^{-6} /K).

3.2.2.1 Thermal expansion coefficient test method

CTE testing methods include:
Differential Scanning Calorimetry (DSC, ASTM E228): Cemented carbide containing 10% Co (5.5×10^{-6} /K±0.1×10^{-6} /K) with a sample size of 10×5×5 mm±0.1 mm, a heating rate of 5°C/min±0.5°C/min, a displacement accuracy of 0.1 μm±0.05 μm , and an error of <2%±0.5%. The ambient temperature is 25°C±2°C.

Thermomechanical analysis (TMA, ASTM E831): cemented carbide containing 8% Co (5.4×10^{-6} /K±0.1×10^{-6} /K) using specimen 5×5×10 mm±0.1 mm, load 0.1 N±0.01 N, temperature resolution 0.1°C±0.05°C, error <3%±0.5%.
Optical interferometry: TiC -containing cemented carbide (5.0×10^{-6} /K±0.1×10^{-6} /K) uses a laser interferometer (wavelength 632.8 nm±0.1 nm, resolution 0.01 μm±0.005 μm), with an error of <5%±1%, which is suitable for high precision.

X-ray diffraction (XRD): CuK α radiation (wavelength 1.5406 Å ± 0.0001 Å) was used to analyze the high temperature CTE (error <5% ± 1%) of cemented carbide containing 10% Co (lattice expansion error <0.1% ± 0.02 %).

For example, nozzles containing TiC pass DSC and TMA tests (5.0×10^{-6} /K±0.1×10^{-6} /K), ensuring a forming life of >5000 hours±500 hours.

3.2.2.2 Factors affecting thermal expansion coefficient

CTE is affected by the following factors:
Composition: Co content increases from 10% to 15%, and CTE increases from 5.5 to 5.8×10^{-6} /K±0.1×10^{-6} /K due to the high CTE of Co phase (12×10^{-6} /K). TiC (15%) decreases to 5.0×10^{-6} /K±0.1×10^{-6} /K due to low CTE (7×10^{-6} /K). Ni (12%) decreases to 5.2×10^{-6} /K±0.1×10^{-6} /K due to the lower CTE of Ni (13×10^{-6} /K).

Process: Sintering temperature (1450°C±10°C) ensures WCCo uniformity (distribution error <5%±1%) and CTE stability; too high temperature (>1550°C) induces Co segregation, increasing 0.2×10^{-6} /K±0.05×10^{-6} /K. HIP (100 MPa±5 MPa) reduces stress (<50 MPa±10 MPa) and decreases 0.1×10^{-6} /K±0.02×10^{-6} /K.

Environment: High temperature (1000°C) increases by 0.2×10^{-6} /K±0.05×10^{-6} /K due to lattice expansion; damp heat (40°C, 90% humidity) no change; high pressure (>100 MPa) decreases by 0.1×10^{-6} /K±0.02×10^{-6} /K; extreme cold (40°C) decreases by 0.1×10^{-6} /K±0.02×10^{-6} /K; radiation (10^{4} Gy) increases by <0.05×10^{-6} /K±0.01×10^{-6} /K.

Sample size: length (>10 mm±0.1 mm) reduces measurement error (<0.05×10^{-6} /K); surface roughness (Ra>0.4 μm) induces stress, increasing 0.1×10^{-6} /K±0.02×10^{-6} /K.

a mold containing 8% Co and TiC (5.0×10^{-6} /K±0.1×10^{-6} /K, HIP process) maintains CTE of 4.9×10^{-6} /K±0.1×10^{-6} /K and deformation <0.005mm±0.001mm during high temperature stamping (600°C) . TiC and HIP are required for optimization .

3.2.3 High temperature stability

The hardness of cemented carbide at 1000°C drops by <30% (HV 1800±30 to 1200±30), which is better than high-speed steel (600°C, HV 500), ceramics (1200°C, HV 800) and titanium alloys (600°C, HV 200). The stability is determined by the high melting point of WC (2870°C±20°C, decomposition energy>500 kJ/mol±10 kJ/mol) and the thermoplasticity of the Co phase (Curie temperature 1120°C±10°C, plastic strain <5%±0.5%). The hardness of cemented carbide containing 10% Co at 1000°C is HV 1300±30, and the wear loss is <0.2mm±0.05mm.

High temperature stability supports extreme working conditions. The wear of the tool containing 8% Co in 1000°C aviation titanium alloy cutting (speed 150 m/min, heat flux density >10 MW/m^2 ± 1 MW/m^2) is <0.15mm±0.03mm, and the life is >10 hours±1 hour, which is better than ceramic tools (wear >0.5mm). The addition of TaC (1%2%) improves the high temperature rigidity (Young's modulus reduction <5%±1%) through solid solution strengthening (lattice strain <2%±0.2%), and the hardness is maintained at HV 1400±30. For example, the nozzle containing TaC operates in a gas turbine (1100°C, gas flow rate >500 m/s±50 m/s), with surface damage <10μm±2μm and life >6000 hours±500 hours, which is better than TaC- free materials (damage >20μm).

Environmental impacts require attention. High temperature oxidation (600°C) generates CoO and WO_3 (weight loss 0.5 mg/cm^2 ± 0.1 mg/cm^2 , oxide layer <2μm±0.5μm), and the hardness decreases by 5%10%±1%; damp heat (40°C, 90% humidity, 168 hours) affects <2%±0.5%; high pressure (>100 MPa) enhances stability, reducing <3%±0.5%; extreme cold (40°C) has no change; radiation (10^4Gy) reduces <1%±0.2%. Cemented carbide containing Cr (0.5%1%) forms a Cr_2O_3 protective layer (thickness <5 nm±1 nm, diffusion coefficient <$10^{-14}$$cm^2$ / s), and the hardness at 1000°C maintains HV 1350±30 . For example, the deformation of a Cr-containing die during high-temperature extrusion (800°C, load >2000 MPa) is <0.01mm±0.002mm, and the service life is increased by 30%±5%.

Optimization requires TaC and coating. CVD coatings (e.g. Al_2O_3 , thickness 5 μm ± 1 μm , thermal conductivity 10 W/m·K ± 2 W/ m·K) reduce the hardness drop by 50%. Tools with Al_2O_3 coatings have a life of > 12 hours ± 1 hour in aerospace engine machining (1000°C, vibration frequency > 10^3 Hz ± 100 Hz), which is better than uncoated tools (life < 4 hours). Cross-domain comparisons show that cemented carbide has better high-temperature stability than steel and titanium alloys, but is inferior to ceramics (Si_3N_4 , hardness > 1000 HV) at ultra-high temperatures (> 1500°C).

3.2.3.1 High temperature stability test method

High temperature stability testing methods include:

High temperature hardness test (ASTM E18): Cemented carbide containing 10% Co (HV 1300±30, 1000°C) using Vickers indenter, load 10 kg±0.1 kg, hold 5 s±0.5 s, error <2%±0.5%. Environmental requirements 1000°C±10°C, atmosphere N_2 (purity>99.99%±0.01%).

Thermogravimetric analysis (TGA, ASTM E1131): Cemented carbide containing 8% Co (oxidation weight gain <2 mg/cm² ± 0.2 mg/ cm² , 1000°C) using a sample of 10×10× 2 mm±0.1 mm, heating 10°C/min±0.5°C/min, mass resolution 0.1 μg±0.05 μg , error <3%±0.5%.

High temperature wear test (ASTM G65): TaC -containing cemented carbide (wear <0.2mm±0.05mm, 1000°C) with grinding wheel friction (speed 1 m/s±0.1 m/s, load 50 N±1 N), error <5%±1%.

High temperature tensile test: Cr-containing cemented carbide (yield strength>1000 MPa±50 MPa, 800°C) uses a specimen diameter of 5 mm±0.1 mm, a rate of 0.1 mm/min±0.01 mm/min, and an error of <5%±1%.

For example, nozzles containing TaC pass high temperature hardness and TGA tests (HV 1400±30, weight gain <1 mg/cm² ± 0.1 mg/cm²) , ensuring a lifetime of >6000 hours ±500 hours.

3.2.3.2 Factors affecting high temperature stability

High temperature stability is affected by the following factors:
Composition: Co content increases from 6% to 15%, and the hardness decreases from 25% to 35% ± 2% (1000°C, HV 1500 to 1000 ± 30) due to Co softening (yield strength < 400 MPa ± 20 MPa). TaC (1% 2%) decreases by < 20% ± 2% due to solid solution strengthening. Cr (0.5% 1%) decreases by < 15% ± 2% due to Cr_2O_3 protective layer.

Process: Sintering temperature (1450°C±10°C) ensures WC stability (decomposition rate <0.1%±0.02%), stability increased by 5%±1%; HIP (100 MPa±5 MPa) eliminates defects, increased by 3%±0.5%. Too high temperature (>1550°C) induces oxidation (weight gain>2 mg/cm² ± 0.2 mg/cm²) , decreased by 5%±1%.

Environment: High temperature oxidation (600°C) decreases by 5%10%±1% due to CoO formation; damp heat (40°C, 90% humidity) affects <2%±0.5%; high pressure (>100 MPa) increases by 3%±0.5%; radiation (10^4Gy) decreases by <1%±0.2%.

Coating: Al_2O_3 coating (5 μm ±1 μm) reduces oxidation (weight gain <0.5 mg/cm² ± 0.1 mg/cm²) and increases stability by 50%±5%; TiN coating (5 μm±1 μm) increases by 30%±3%.

with Cr and Al_2O_3 coating (HV 1350±30, 1000°C) has a deformation of <0.01mm±0.002mm and a service life of >6000h±500h during high temperature extrusion (800°C). TaC and coating are required for optimization.

3.2.4 Thermal shock resistance

The thermal shock resistance of cemented carbide is evaluated by thermal shock test (500°C water cooling, 100 times, ASTM C1525), and the crack length is <5μm±1μm, which is better than ceramic (>10μm) and alumina (>15μm). The thermal shock resistance is determined by low CTE (5.5×10^{-6} /K±0.1×10^{-6} /K), high thermal conductivity (100 W/m·K±5 W/ m·K) and high strength (>4000 MPa±100 MPa), and the thermal stress is <200 MPa±20 MPa. The crack depth of cemented carbide containing 12% Co in thermal cycle (25800°C, 1000 times, temperature difference >500°C±10°C) is <3μm±0.5μm.

Thermal shock resistance supports thermal cycling conditions. The mold containing 10% Co has a crack rate of <0.5% and a life of >5000 hours ±500 hours in high-temperature stamping (600°C, frequency $>10^4$ times/hour, temperature difference >400°C±10°C), which is better than steel molds (crack rate >5%). Adding Cr (0.5%1%) to form a Cr_2O_3 protective layer (thickness <5 nm±1 nm), the thermal shock resistance is improved by 15%±2%, and the crack initiation rate is reduced by 20%±3%. For example, the surface damage of the nozzle containing Cr is <5μm±1μm in the thermal cycle of the gas turbine (1100°C, gas flow rate >500 m/s±50 m/s), and the life is extended by 35%±5%.

Environmental influences include high temperature oxidation (600°C, CoO formation , thickness <2μm±0.5μm, thermal shock resistance decreased by 5%±1%), damp heat (40°C, 90% humidity, decreased by <2%±0.5%), high pressure (>100 MPa, increased by 3%±0.5%), extreme cold (40°C, crack rate increased by 3%±0.5%), and radiation (10^4 Gy, decreased by <1%±0.2%). Ni-containing cemented carbide (12% Ni, crack <3μm±0.5μm) is more stable in nuclear power steam (500°C, 10 MPa, steam flow rate >100 m/s±10 m/s). For example, a Ni-containing pipeline has been in operation for 3 years with cracks <3μm±0.5μm, which is better than Co-containing materials (cracks >5μm).

Optimization requires high Co (10%12%) and coating. CVD coatings (such as TiN , 5 μm±1 μm , thermal conductivity 20 W/m·K±2 W/ m·K) reduce the crack rate by 50%±5%. The tool life of TiN -coated tools in thermal cycle cutting (800°C, vibration frequency>10^3 Hz ± 100 Hz) is>10 hours±1 hour, which is better than uncoated tools (life<4 hours). Cross-domain comparisons show that cemented carbide has better thermal shock resistance than ceramics and titanium alloys, but is inferior to carbon fiber composites (cracks<1μm) under ultra-high thermal shock .

3.2.4.1 Thermal shock resistance test method

Thermal shock resistance testing methods include:
Thermal shock test (ASTM C1525): Cemented carbide containing 12% Co (crack <5μm±1μm) using specimen 10×10× 5 mm±0.1 mm, 500°C water cooling (temperature difference>450°C±10°C), 100 times, crack detection using SEM (resolution <5 nm±1 nm), error

<3%±0.5%.

Thermal cycle fatigue test: Cemented carbide containing 10% Co (crack <3μm±0.5μm) was cycled at 25800°C for 1000 times, with a temperature difference of >500°C±10°C and an error of <5%±1%.

Ultrasonic testing (ASTM E588): For Cr-containing cemented carbide (crack depth <5μm±1μm), longitudinal wave (frequency 5 MHz±0.1 MHz, wave speed 6 km/s±0.1 km/s) is used, with an error of <5%±1%.

Infrared thermal imaging: Ni-containing cemented carbide (crack <3μm±0.5μm) uses an infrared camera (resolution 0.1°C±0.05°C) to analyze the thermal stress distribution (error <5%±1%).

For example, nozzles containing Cr pass thermal shock and ultrasonic tests (crack <5μm±1μm), ensuring a gas turbine life of >5000 hours±500 hours.

3.2.4.2 Factors affecting thermal shock resistance

Thermal shock resistance is affected by the following factors:
Composition: Co content increases from 10% to 12%, thermal shock resistance increases by 15%±2% due to enhanced plasticity (strain <5%±0.5%). TiC (15%) decreases by 10%±1% due to reduced CTE (5.0×10^{-6} /K±0.1×10^{-6} /K) but reduced thermal conductivity (85 W/m·K±5 W/ m·K). Cr (0.5%1%) increases by 15%±2% due to the Cr_2O_3 protective layer.

Process: Sintering temperature (1450°C±10°C) improves uniformity and thermal shock resistance by 5%±1%; HIP (100 MPa±5 MPa) reduces defects by 10%±1%. Rapid cooling (>10°C/min) induces stress (>100 MPa±10 MPa), which decreases by 5%±1%.
Environment: High temperature oxidation (600°C) decreases by 5%±1% due to CoO formation; damp heat (40°C, 90% humidity) decreases by <2%±0.5%; high pressure (>100 MPa) increases by 3%±0.5%; extreme cold (40°C) decreases by 3%±0.5%; radiation (10^4Gy) decreases by <1%±0.2%.
Coating: TiN coating (5 μm±1 μm) reduces thermal stress (<150 MPa±20 MPa), increased by 50%±5%; Al_2O_3 coating increases by 30%±3%.

For example, a tool with 10% Co and TiN coating (crack < 3μm ± 0.5μm) has a life of > 10 hours ± 1 hour in thermal cycle cutting (800°C). Optimization requires high Co and TiN coatings.

3.3 Chemical stability of cemented carbide

The chemical stability of cemented carbide refers to its ability to resist chemical reactions or corrosion in various environments (such as acid, alkali, high temperature, wet heat, etc.), which is mainly determined by the chemical properties of tungsten carbide (WC) hard phase and cobalt (Co) or nickel (Ni) bonding phase. WC has excellent oxidation resistance and corrosion resistance, and is chemically inert, but it may decompose or oxidize to form WO_3 at high temperatures (>800°C) .

The Co phase is relatively active and is prone to corrosion in acidic (pH<4, such as HCl, H_2SO_4) or wet and hot environments (40°C, 90% humidity), with a weight loss rate of 0.1-0.2 mg/cm² /year, while the Ni phase is more corrosion resistant (weight loss <0.05 mg/cm² /year).

The chemical stability of cemented carbide is affected by composition and process: reducing the Co content (6%-8%) or adding Cr and TiC (0.5%-1%) can form a protective layer (such as Cr_2O_3), which improves corrosion resistance by about 10%-15%; high temperature sintering (1350-1450°C) and HIP process reduce porosity (<0.05%), reduce corrosion channels, and improve stability by about 5%-10%. In practical applications, Ni-containing cemented carbide has excellent stability in marine environments (salinity 3.5%, 50 MPa), with a strength drop of <1% and a service life of more than 3 years; at high temperature (1000°C), the oxidation weight gain of TiC -containing cemented carbide is <0.08 mg/cm² , which is better than the pure Co system (>0.1 mg/cm²). The current date and time is May 21, 2025 10:10 AM JST.

of cemented carbide ensures that it can serve for a long time in corrosive media, high-temperature oxidation and complex chemical environments, and is used in chemical industry, ocean, nuclear power and deep sea.

3.3.1 Corrosion resistance of cemented carbide

Cemented carbide has excellent corrosion resistance in acidic (pH 24), neutral (pH 68), and alkaline (pH 1012) environments, and the chemical inertness of the WC phase (dissolution rate $<10^{-6}$ g/cm² · h±10^{-7} g/cm² · h) is the key. The corrosion rate of cemented carbide containing 10% Co in a neutral environment (3.5% NaCl, containing Cl^- 19 g/L) is <0.05 mm/year±0.01 mm/year, and the corrosion potential is 0.3 V±0.02 V (vs. SCE), which is better than high-strength steel (0.6 V, 0.5 mm/year) and stainless steel (0.2 mm/year). In an acidic environment (pH 3, H_2SO_4 , concentration 1 mol/L) , the Co phase dissolved (weight loss 0.10.5 mg/cm² ± 0.05 mg/cm²) and the corrosion rate increased to 0.1 mm /year ± 0.02 mm/year.

The weight loss of Ni-containing cemented carbide (12% Ni) in salt spray test (ASTM B117, 168 hours, 35°C±1°C) is <0.1 mg/cm² ± 0.02 mg/cm² , and the corrosion rate in alkaline environment (pH 12, NaOH, concentration 0.1 mol/L) is <0.02 mm/year±0.005 mm/year, which is better than Co-containing materials (0.05 mm/year±0.01 mm/year). Adding Cr (0.5%1%) forms a Cr_2O_3 passivation layer (thickness <5 nm±1 nm, resistivity> $10^6\Omega$ ·cm± 10^5 Ω·cm), the acid corrosion rate dropped to 0.01 mm/year±0.002 mm/year.

For example, valves containing NiCr have been operating in the deep sea (pH 8, salinity 3.5%, 5000 m depth) for 5 years with a corrosion depth of <5μm±1μm, which is better than stainless steel (depth>50μm, life <2 years).

The environmental influence is significant. Wet heat (40°C, 90% humidity, 168 hours) intensifies Co phase corrosion (weight loss increased by 10%15%±2%, corrosion current density>1 μA / cm²

± 0.1 μA / cm²) ; high pressure (>100 MPa, deep sea) reduces ion diffusion (diffusion coefficient <10^{-10}cm² / s ±10^{-11}cm² / s), and the corrosion rate decreases by 5%±1 % ; extreme cold (40°C) slows down the reaction (reaction rate decreases <50%±5%), and decreases by 3%±0.5%; radiation (10^4Gy) induces surface defects, and increases by 2%±0.3%. Cemented carbide containing Mo (0.5%1%) forms a MoO_2 protective layer (thickness <3 nm±0.5 nm), and the acid corrosion rate is <0.015 mm/year±0.003 mm/year.

For example, the surface damage of a reactor containing NiMo after operating in HCl (pH 2, concentration 1 mol/L) for 3 years was <3μm±0.5μm, which is better than that of Co-containing materials (damage >10μm).

Corrosion resistance supports chemical industry and ocean. The pump body containing 10% Co was operated in a chemical plant (pH 4, H_2SO_4 , flow rate>5m/s±0.5m/s) for 2 years , with corrosion depth <10μm±2μm and life>2year±0.2year; the lining containing Ni increased its life by 40%±5% in the marine environment (pH 8, salinity 3.5%). Cross-field comparison shows that cemented carbide has better corrosion resistance than steel and titanium alloy (0.3mm/year), but is inferior to ceramics in strong oxidizing acids (such as HNO_3 , concentration>5mol/L) (weight loss<0.01mg/cm²) .

3.3.1.1 Corrosion resistance test method

Corrosion resistance testing methods include:
Electrochemical test (ASTM G59): Cemented carbide containing 10% Co (corrosion rate <0.05 mm/year ± 0.01 mm/year) using a three-electrode system (reference electrode SCE, scan rate 1 mV/s ± 0.1 mV/s, potential range ± 250 mV ± 10 mV), corrosion current error <1% ± 0.2%, total error <2% ± 0.5%. Environmental requirements 25°C ± 2°C, electrolyte 3.5% NaCl.

Salt spray test (ASTM B117): Cemented carbide containing 12% Ni (weight loss <0.1 mg/cm² ± 0.02 mg/ cm²) at 35°C±1°C, 5% NaCl spray, 168 hours, mass resolution 0.1 mg±0.05 mg, error <3%±0.5%.
Immersion test (ASTM G31): Cr-containing cemented carbide (corrosion rate <0.01 mm/year ± 0.002 mm/year) using pH 2 H_2SO_4 , 168 hours, temperature 25°C ± 2°C, weight loss error <0.01 mg/cm² ± 0.005 mg/cm² , error <5% ± 1%.

XPS surface analysis: Mo-containing cemented carbide (corrosion layer <3μm±0.5μm) uses AlKα radiation (1486.6 eV±0.1 eV, resolution 0.1 eV±0.05 eV) to analyze the passivation layer (error <5%±1%).

For example, valves containing NiCr pass electrochemical and salt spray tests (corrosion rate <0.02 mm/year ±0.005 mm/year, weight loss <0.1 mg/cm² ± 0.02 mg/cm²) , ensuring a deep-sea life of >5 years ±0.5 years.

3.3.1.2 Factors affecting the corrosion resistance of cemented carbide

Corrosion resistance is affected by:

Element

When the Co content increases from 10% to 15%, the corrosion rate in a neutral environment (3.5% NaCl, pH 8) increases from 0.05 to 0.07 mm/year ± 0.01 mm/year, due to the enhanced electrochemical activity of the Co phase (corrosion current density increases from 1 to 1.5 μA / cm^2 ± 0.1 μA / cm^2) . Ni substitution for Co (12% Ni) reduces the corrosion rate to 0.02 mm/year ± 0.005 mm/year, due to the formation of a stable NiO passivation layer (thickness <3 nm ± 0.5 nm, resistivity > 10^7 Ω·cm±10^6 Ω·cm). Cr addition (0.5%1%) drops to 0.01 mm/year±0.002 mm/year, because the Cr_2O_3 protective layer (binding energy>400 kJ/mol±10 kJ/mol) inhibits ion diffusion (diffusion coefficient<10^{-14} cm^2 /s±10^{-15} cm^2 /s). Mo (0.5%1%) forms MoO_2 (thickness<3 nm±0.5 nm), and the corrosion rate in acidic environment (pH 2, HCl) drops to 0.015 mm/year±0.003 mm/year.

For example, a valve containing NiCr (corrosion rate 0.01 mm/year ± 0.002 mm/year) operated in the deep sea (5000 m, salinity 3.5%) for 5 years with surface damage of < 5 μm ± 1 μm.

Technology

Sintering temperature (1450°C±10°C) ensures WCCo interface bonding (bonding strength>50 MPa±5 MPa), reduces Co exposure (exposed area<5%±1%), and reduces corrosion rate by 3%±0.5%. Hot isostatic pressing (HIP, 100 MPa±5 MPa) eliminates pores (porosity<0.1%±0.02%), reduces corrosion paths, and reduces corrosion rate by 5%±1%. Excessive temperature (>1550°C) induces Co segregation (segregation rate<5%±1%), and increases corrosion rate by 10%±2%. Surface polishing (Ra<0.2 μm±0.05 μm) reduces reactive sites (surface energy<1 J/m^2 ± 0.1 J/ m^2), reducing corrosion rate by 2%±0.3%. For example, a pump body containing 10% Co and HIP process (corrosion rate 0.04 mm/year ± 0.01 mm/year) is operated in a chemical plant (pH 4) with a service life of > 2 years ± 0.2 years.

Environment

Wet heat (40°C, 90% humidity, 168 hours) intensifies Co phase corrosion (weight loss increased by 10%15%±2%, corrosion depth <2μm±0.5μm); high pressure (>100 MPa, deep sea) inhibits ion migration, reducing by 5%±1%; extreme cold (40°C) slows down reaction kinetics (activation energy>100 kJ/mol±5 kJ/mol), reducing by 3%±0.5%; radiation (10^4 Gy, γ-ray) induces surface defects (vacancy density <10^{15} /cm^3), increasing by 2%±0.3%; strong oxidizing acid (such as HNO_3 , 5 mol/L) induces WC dissolution (weight loss>0.5 mg/cm^2 ± 0.1 mg/cm^2), increasing by 20%±3%. Mo-containing cemented carbide operates in HCl (pH 2), and the corrosion rate is maintained at 0.015 mm/year±0.003 mm/year.

Electrochemical conditions

Potential (>0.3 V vs. SCE) triggers Co anodic dissolution (dissolution rate>10^{-6} g/cm^2 · h±10^{-7}

g/cm ² · h), and the corrosion rate increases by 10%±2%; low pH (<4) accelerates H^+ attack (reaction rate>10^{-5} mol/cm ² · s±10^{-6} mol/cm ² · s), increasing by 15%±2%. For example, the corrosion rate of Ni-containing electrodes (corrosion potential 0.2 V±0.02 V) operating in electrolyte (pH 3) is <0.02 mm/year±0.005 mm/year.

Surface treatment

CVD coating (such as CrN , 5 μm±1 μm , resistivity>10^8 Ω·cm±10^7 Ω·cm) reduces the corrosion rate by 50%±5% due to the isolation medium; polishing (Ra<0.1 μm±0.02 μm) reduces by 3%±0.5%. The lining with CrN coating has been operating in a marine environment (pH 8) for 3 years, and the corrosion depth is <3μm±0.5μm.

Optimizing corrosion resistance requires Ni/Cr/Mo addition and HIP process. For example, the life of a valve containing 12% Ni and 0.5% Cr (corrosion rate 0.01 mm/year ± 0.002 mm/year) operating in deep-sea oil and gas (5000 m, pH 8) is increased by 40% ± 5%.

3.3.2 Oxidation resistance of cemented carbide

The oxidation resistance of cemented carbide is determined by the chemical stability of WC (oxidation enthalpy <800 kJ/mol±20 kJ/mol) and the oxidation tendency of Co phase (CoO formation, enthalpy <200 kJ/mol±10 kJ/mol). At 700°C, the oxidation weight of cemented carbide containing 10% Co increases by 0.5 mg/cm² ± 0.1 mg/cm² , and the thickness of the oxide layer is <2μm±0.5μm; at 1000°C, the weight increases by 2 mg/cm² ± 0.2 mg/ cm² , and the thickness of the oxide layer is <10μm±2μm, which is better than high-strength steel (700°C, weight increase>5 mg/cm²) and titanium alloy (700°C, weight increase>3 mg/cm²) .

Oxidation resistance supports high temperature working conditions. When cutting aviation titanium alloy (1000°C, heat flux >10 MW/m² ± 1 MW/m², O_2 partial pressure 0.21 atm±0.01 atm), the oxidation depth of the tool containing 8% Co is < 5μm ± 1μm , the wear amount is <0.15mm±0.03mm, and the life is >10 hours±1 hour, which is better than ceramic tools (oxidation depth >20μm). Adding TiC (15 %) to form a TiO_2 protective layer (thickness <3μm±0.5μm, diffusion coefficient <10^{-14}cm² / s ± 10^{-15}cm² / s), the weight gain at 1000° C is reduced to 1 mg/cm² ± 0.1 mg/ cm² .

For example, a nozzle containing 15% TiC operated in a gas turbine (1100°C, gas flow rate >500 m/s±50 m/s, O_2 content 20%±1%) for 5000 hours, with an oxide layer thickness of <8μm±2μm and a deformation of <0.01mm±0.002mm, which is better than that of TiC- free material (oxide layer >15μm).

Environmental impacts require attention. Wet heat (40°C, 90% humidity, 168 hours) induces micro-oxidation of CoO (weight gain <0.1 mg/cm² ± 0.02 mg/cm²) , and the oxidation resistance decreases by <2%±0.5%; high temperature steam (500°C, 10 MPa, H_2O partial pressure>0.9 atm±0.01 atm) accelerates the formation of WO_3 (weight gain increased by 10%±2%, oxide layer <5μm±1μm);

high pressure (>100 MPa) inhibits oxygen diffusion, decreasing by 5%±1%; radiation (10^4Gy) induces surface defects, increasing by 2%±0.3%. Cemented carbide containing Cr (0.5%1%) forms a Cr_2O_3 protective layer (thickness < 5 nm±1 nm, resistivity> $10^6\Omega$ ·cm± 10^5 Ω·cm), the weight gain at 1000°C is reduced to 0.8 mg/cm² ± 0.1 mg/cm² . For example, in high temperature extrusion (800°C, O_2 partial pressure 0.21 atm±0.01 atm), the oxidation depth of Cr-containing molds is <3μm±0.5μm, and the service life is increased by 30%±5%.

Optimization requires Cr/ TiC addition and coating. CVD coatings (such as Al_2O_3 , 5 μm±1 μm , thermal conductivity 10 W/m·K±2 W/ m·K , oxidation enthalpy <1600 kJ/mol±50 kJ/mol) will reduce weight gain by 60%±5%. Tools with Al_2O_3 coating have an oxidation depth of <3μm±0.5μm and a life of >12 hours±1 hour in aerospace engine machining (1000°C, vibration frequency >10^3 Hz ± 100 Hz), which is better than uncoated tools (oxidation depth >10μm, life <4 hours). Cross-domain comparisons show that cemented carbide has better oxidation resistance than steel and titanium alloys, but is inferior to ceramics (Si_3N_4 , weight gain <0.5 mg/cm²) at ultra-high temperatures (>1200°C).

3.3.2.1 Inspection method for oxidation resistance of cemented carbide

Antioxidant testing methods ensure high temperature stability assessment, common techniques include:

Thermogravimetric analysis (TGA, ASTM E1131)
Cemented carbide containing 10% Co (700°C, weight gain 0.5 mg/cm² ± 0.1 mg/ cm²) uses a sample of 10×10× 2 mm±0.1 mm, a heating rate of 10°C/min±0.5°C/min, a mass resolution of 0.1 μg±0.05 μg , an atmosphere of air (O_2 partial pressure 0.21 atm±0.01 atm), and an error of <2%±0.5%.

High temperature exposure test (ISO 21608)
TiC - containing cemented carbide (1000°C, weight gain <1 mg/cm² ± 0.1 mg/cm²) , the specimen was 20×10×5 mm±0.1 mm, exposed for 168 hours, with a temperature fluctuation of <±5°C and an error of <3%±0.5%.
E2108): Cr-containing cemented carbide (oxide layer thickness <8μm±2μm) uses AlKα radiation (1486.6 eV±0.1 eV, resolution 0.1 eV±0.05 eV) to analyze the oxide composition (Cr_2O_3 / WO_3 , error <5%±1%).

Scanning electron microscopy (SEM, ASTM E986)
the oxide layer of cemented carbide with Al_2O_3 coating (oxidation depth < 3μm ±0.5μm) was analyzed using backscattered electron mode with a resolution of <5 nm±1 nm (error <5%±1%).

Spectroscopic Ellipsometry
For cemented carbide containing 10% Co (oxide layer <10μm±2μm), the wavelength is 300800 nm±1 nm and the incident angle is 70°±0.5° to measure the oxide layer thickness (error <5%±1%).

The test requires controlled atmosphere (O_2 purity > 99.9% ± 0.1%) and temperature (fluctuation < ± 5°C). For example, nozzles containing Cr pass TGA and XPS tests (1000°C, weight gain 0.8 mg/cm² ± 0.1 mg/cm² , oxide layer < 8μm ± 2μm), ensuring a gas turbine life of > 5000 hours ± 500 hours.

3.3.2.2 Factors affecting antioxidant activity

Antioxidant activity is affected by the following factors:
Composition : Co content increases from 10% to 15%, and the weight gain at 1000°C increases from 2 to 2.5 mg/cm² ± 0.2 mg/ cm² due to the increased rate of CoO formation (reaction rate>10^{-5} g/cm² · s ±10^{-6} g/cm² · s). TiC (15%) decreases to 1 mg/cm² ± 0.1 mg/cm² due to the TiO_2 protective layer (diffusion coefficient<10^{-14} cm² / s). Cr (0.5%1%) decreases to 0.8 mg/cm² ± 0.1 mg/cm² due to the formation of Cr_2O_3 (binding energy>400 kJ/mol±10 kJ/mol) . For cemented carbide with Al_2O_3 coating (5 μm ±1 μm) , it drops to 0.3 mg/cm² ± 0.05 mg/ cm² .

Process : Sintering temperature (1450°C±10°C) ensures WC stability (decomposition rate <0.1%±0.02%), and weight gain decreases by 3%±0.5%; HIP (100 MPa±5 MPa) reduces porosity (<0.1%±0.02%), and decreases by 5%±1%. Excessive temperature (>1550°C) induces Co oxidation (weight gain increases by 10%±2%). Coating deposition (CVD, 800°C±10°C) forms dense Al_2O_3 (porosity <0.5%±0.1%), and decreases by 60%±5% .

Environment : High temperature (1000°C) increases weight by 20%±3% due to O_2 diffusion (diffusion coefficient>10^{-12} cm²/s±10^{-13} cm² / s) ; moist heat (40 °C, 90% humidity) induces micro-oxidation, increasing by <2%±0.5%; steam (500°C, 10 MPa) increases weight by 10%±2% due to WO_3 generation ; high pressure (>100 MPa) decreases weight by 5%±1%; radiation (10^4Gy) increases weight by 2%±0.3%.

Surface condition : Polishing (Ra<0.2 μm±0.05 μm) reduces oxidation sites (surface energy <1 J/m² ± 0.1 J/ m²) by 3%±0.5%; rough surface (Ra>0.4 μm) increases by 5%±1%.
Atmosphere : Low O_2 partial pressure (<0.1 atm±0.01 atm) decreases weight by 50%±5%; H_2O-containing atmosphere (partial pressure>0.5 atm±0.01 atm) increases weight by 10%±2%.

For example, a tool containing Cr and Al_2O_3 coating (1000°C, weight gain 0.3 mg/cm² ± 0.05 mg/cm²) has an oxidation depth of <3μm±0.5μm and a life of >12 hours±1 hour in aviation cutting . Optimization requires Cr addition and Al_2O_3 coating.

3.4 Electrical and magnetic properties of cemented carbide

Electrical and magnetic properties support the application of cemented carbide in electrical discharge machining (EDM), magnetic detection, nuclear power shielding and aerospace sensors. This section analyzes the electrical conductivity and Co phase magnetic properties.

3.4.1 Electrical conductivity of cemented carbide

The resistivity of cemented carbide is 20 μΩ·cm±5 μΩ·cm , and the conductivity is 510 MS/m±0.5 MS/m, which is between copper (58 MS/m) and ceramic (<0.1 MS/m), and is determined by WC (resistivity 15 μΩ·cm±2 μΩ·cm , electron mobility>2×10^{4} cm^{2} /V·s±10^{3} cm^{2} /V·s) and Co (resistivity 6 μΩ·cm±1 μΩ·cm). The conductivity of cemented carbide containing 10% Co is 8 MS/m±0.5 MS/m, and that containing 12% Ni rises to 10 MS/m±0.5 MS/m, because Ni has higher electron conductivity (mobility>1.5×10^{4} cm^{2} /V·s±10^{3} cm^{2} /V·s).

Electrical conductivity supports electromachining and electrolysis. In EDM (current density>10^{4} A/cm^{2} ± 10^{3} A/cm^{2} , pulse width 0.1 ms±0.01 ms), the processing speed of cemented carbide molds containing 10% Co is>0.5 mm/min±0.05 mm/min, and the surface roughness Ra<0.2μm±0.05μm is better than that of steel molds (Ra>0.5μm). The electrode containing 8% Ni runs in the electrolyte (pH 3, H_2SO_4 , concentration 1 mol/L) for 5000 hours, and the conductivity is maintained at 9 MS/m±0.5 MS/m, and the corrosion depth is <5μm±1μm.

For example, an electrode containing 12% Ni has an efficiency of >95%±2% and a lifespan of >5000 hours±500 hours in a new energy electrolyzer (current density >500 A/m^2 ± 50 A/ m^2 , temperature 60°C±2°C).

At high temperature (600°C), the conductivity drops to 7 MS/m±0.5 MS/m (a decrease of <15%±2%) due to electron scattering (mobility decreases <10^{4} cm^{2} / V ·s ±10^{3} cm^{2} /V·s); at damp heat (40°C, 90% humidity, 168 hours), the conductivity drops by <3%±0.5% due to Co micro-corrosion (weight loss <0.1 mg/cm^{2} ± 0.02 mg/cm^{2}); at high pressure (>100 MPa, deep sea), the conductivity increases by 2%±0.3% due to lattice compression (lattice constant decreases by 0.1%±0.02%); at extreme cold (40°C), the conductivity increases by 3%±0.5%; and at radiation (10^{4} Gy) the conductivity drops by <1%±0.2% due to surface defects. Cemented carbide containing Cr (0.5%1%) forms Cr_2O_3 (resistivity>10^{6} Ω·cm±10^{5} Ω·cm), the surface conductivity decreased by 5%±1%, but the core was stable.

For example, the conductivity of the Cr-containing electrode was maintained at 8 MS/m±0.5 MS/m after operating in a marine environment (pH 8, salinity 3.5%, 5000 m) for 3 years, which is better than that of the Co-containing material (decrease >5%±1%).

Optimization requires Ni addition and high density (>99%±0.1%). Wires containing 12% Ni have a resistivity change of <2%±0.5% and a signal error of <0.1%±0.02% in aerospace sensors (500°C, vibration frequency >10^{3} Hz ± 100 Hz). Cross-domain comparisons show that cemented carbide is more conductive than ceramics and glass, but inferior to copper and silver (>50 MS/m).

3.4.1.1 Test method for conductivity of cemented carbide

Conductivity testing methods ensure electrical performance evaluation, common techniques include:

Four-probe method (ASTM B193)

containing 10% Co (8 MS/m±0.5 MS/m) uses a sample of 20×10×2 mm±0.1 mm, a current of 1 A±0.01 A, a probe spacing of 1 mm±0.01 mm, a voltage resolution of 0.1 μV±0.05 μV , and an error of <2%±0.5%. The environmental requirements are 25°C±2°C, and the surface Ra<0.2 μm±0.05 μm .

Eddy Current Test (ASTM E1004)

Cemented carbide containing 12% Ni (10 MS/m±0.5 MS/m) uses a frequency of 10 kHz±0.1 kHz, a coil diameter of 5 mm±0.1 mm, a signal resolution of 0.1 μS±0.05 μS , an error of <3%±0.5%, and is suitable for complex shapes.

Resistivity meter (ASTM D257)

The cemented carbide containing 8% Co (20 μΩ·cm±5 μΩ·cm) has a specimen diameter of 10 mm±0.1 mm, a thickness of 2 mm±0.1 mm, an accuracy of 0.1 μΩ·cm±0.05 μΩ·cm , and an error of <5%±1%.

Hall Effect Test

For Ni-containing cemented carbide (mobility > 1.5×10^{4} $cm^{2}/V\cdot s\pm10^{3}$ $cm^{2}/V\cdot s$), a magnetic field of 0.5 T±0.01 T and a current of 10 mA±0.1 mA are used with an error of <5%±1%, which is suitable for electronic behavior analysis.

For example, electrodes containing 12% Ni pass four-probe and eddy current tests (10 MS/m±0.5 MS/m) to ensure a cell life of >5000 hours±500 hours.

3.4.1.2 Factors affecting conductivity of cemented carbide

Electrical conductivity is affected by:

Element

As the Co content increases from 10% to 15%, the conductivity increases from 8 to 9 MS/m±0.5 MS/m, due to the high conductivity of the Co phase (resistivity 6 μΩ·cm±1 μΩ·cm). Ni (12%) increases to 10 MS/m±0.5 MS/m, due to the higher electron mobility of Ni. TiC (15%) decreases to 7 MS/m±0.5 MS/m, due to the high resistivity of TiC (>50 μΩ·cm±5 μΩ·cm). Cr (0.5%1%) decreases to 7.5 MS/m±0.5 MS/m, due to the insulation of Cr_2O_3 (resistivity>10^{6} Ω·cm±10^{5} Ω·cm ）.

Technology

Sintering temperature (1450°C±10°C) improves WCCo contact (contact area>90%±2%), and conductivity increases by 3%±0.5%; HIP (100 MPa±5 MPa) reduces porosity (<0.1%±0.02%), increasing by 2%±0.3%. Excessive temperature (>1550°C) induces Co segregation, decreasing by 3%±0.5%. Polishing (Ra<0.2 μm±0.05 μm) reduces contact resistance (<0.1 μΩ±0.02 μΩ),

increasing by 1%±0.2%.

Environment

High temperature (600°C) decreases by 15%±2% due to electron scattering; damp heat (40°C, 90% humidity) decreases by <3%±0.5% due to Co corrosion; high pressure (>100 MPa) increases by 2%±0.3% due to lattice compression; extreme cold (40°C) increases by 3%±0.5%; radiation (10^4 Gy) decreases by <1%±0.2%.

Sample geometry : Thickness (>2 mm±0.1 mm) reduces boundary resistance (<0.1 μΩ±0.02 μΩ), increasing by 2%±0.3%; surface roughness (Ra>0.4 μm) induces scattering, decreasing by 1%±0.2%.

Electric field conditions : High frequency AC (>10 kHz±0.1 kHz) induces skin effect (depth <0.1 mm±0.01 mm), reducing by 2%±0.3%; conductivity is stable under DC.

For example, a wire with 12% Ni and HIP process (10 MS/m ± 0.5 MS/m) maintains conductivity of 9.8 MS/m ± 0.5 MS/m in an aerospace sensor (500°C) with a signal error of < 0.1% ± 0.02%. Optimization requires Ni addition and HIP.

3.4.2 Magnetic properties of cemented carbide

The magnetic properties of cemented carbide are mainly determined by the Co phase (face-centered cubic FCC, Curie temperature 1120°C±10°C), with a saturation magnetization of 1400 kA/m±50 kA/m (containing 10% Co), a magnetic permeability of 1.05±0.01, and a coercive force of 1020 kA/m±1 kA/m. Cemented carbide containing 12% Ni is close to non-magnetic (saturation magnetization <10 kA/m±2 kA/m, magnetic permeability <1.01±0.01) because Ni is weakly ferromagnetic (magnetic moment 0.6 μ_B /Ni±0.1 μ_B /Ni).

Magnetism supports detection and adsorption. In precision machining (adsorption force > 100 N/cm ^{2} ± 10 N/cm ^{2} , positioning deviation < 0.01mm ± 0.002mm), the adsorption efficiency of carbide fixtures containing 6% Co is > 98% ± 1%, which is better than steel fixtures (deviation > 0.05mm). In nuclear magnetic resonance (MRI, magnetic field 1.5 T ± 0.1 T) equipment, the interference magnetic field of carbide containing Ni is < 0.1 μT ± 0.02 μT , which is better than Co-containing materials (interference > 1 μT). For example, in space navigation (vibration frequency > 10^3 Hz ± 100 Hz), the magnetic interference of sensor housings containing 12% Ni is < 0.05 μT ± 0.01 μT and the signal error is < 0.1% ± 0.02%.

At high temperature (600°C) , the magnetization intensity decreases by 20%±2% (to 1100 kA/m±50 kA/m) due to the proximity of Co Curie point (thermal vibration>10^{12} Hz ± 10^{11} Hz); at damp heat (40°C, 90% humidity, 168 hours), the magnetization intensity decreases by <2%±0.5% due to Co micro-corrosion (weight loss<0.1 mg/ cm² ± 0.02 mg/cm²) ; at high pressure (>100 MPa), the magnetization intensity increases by 1%±0.3% due to lattice compression (lattice constant decreases

by 0.1%±0.02%); at extreme cold (40°C), the magnetization intensity increases by 2%±0.3% due to enhanced magnetic moment; at radiation (10^4 Gy), the magnetization intensity decreases by <1%±0.2% due to surface defects. The magnetization intensity of cemented carbide containing Cr (0.5%1%) decreases by 5%±1% due to the antiferromagnetic nature of Cr (magnetic moment <0.1 μ_B /Cr±0.02 μ_B /Cr).

For example, a sensor housing containing Cr has been operating in aviation (500°C, O_2 partial pressure 0.21 atm±0.01 atm) for 3 years with magnetic interference <0.05 μT±0.01 μT , which is better than Co-containing materials (interference >0.1 μT).

Optimization requires Ni to replace Co and low Cr addition. In magnetic grinding (magnetic field 0.5 T±0.01 T, grinding speed>1 m/s±0.1 m/s), the efficiency of cemented carbide containing 10% Co is improved by 20%±3%, and the surface roughness Ra<0.1μm±0.02μm. Cross-field comparison shows that the magnetic properties of cemented carbide are better than non-magnetic ceramics (magnetic permeability <1.001), but inferior to pure Co (>2000 kA/m).

3.4.2.1 Magnetic testing method for cemented carbide

Magnetic testing methods ensure magnetic performance evaluation, common techniques include:

Vibrating Sample Magnetometer (VSM, ASTM A894)
Cemented carbide containing 10% Co (1400 kA/m±50 kA/m) uses a specimen of 5×5×2 mm±0.1 mm, a magnetic field of 1 T±0.01 T, a vibration frequency of 55 Hz±1 Hz, a magnetization intensity resolution of 0.1 kA/m±0.05 kA/m, and an error of <2%±0.5%. The environmental requirement is 25°C±2°C.

Fluxmeter (ASTM A773)
The cemented carbide containing 6% Co (coercivity 10 kA/m±1 kA/m) has a specimen diameter of 10 mm±0.1 mm, a thickness of 2 mm±0.1 mm, an accuracy of 0.1 kA/m±0.05 kA/m, and an error of <3%±0.5%.

Hall Effect Test (ASTM F76)
For Ni-containing cemented carbide (interference <0.1 μT±0.02 μT), a magnetic field of 0.5 T±0.01 T, a current of 10 mA±0.1 mA, a voltage resolution of 0.1 μV±0.05 μV and an error of <5%±1% are used.

Magnetic force microscopy (MFM)
The hard alloy containing 10% Co (magnetic domain size <1μm±0.2μm) uses a probe resolution of <10 nm±2 nm, a scanning range of 10×10 μm±0.1 μm , and an error of <5%±1%, which is suitable for microscopic magnetic analysis.

For example, the sensor housing containing 12% Ni passes VSM and Hall tests (interference <0.1

μT±0.02 μT), ensuring a space navigation life of >3 years±0.3 years.

3.4.2.2 Factors affecting the magnetic properties of cemented carbide

Magnetic properties are affected by:

Element

When the Co content increases from 6% to 15%, the magnetization increases from 1000 to 1600 kA/m±50 kA/m, due to the enhanced magnetic moment of Co (1.7 μ_B /Co±0.1 μ_B /Co). Ni (12%) decreases to <10 kA/m±2 kA/m, due to the weak magnetism of Ni (0.6 μ_B /Ni±0.1 μ_B /Ni). Cr (0.5%1%) decreases to 1300 kA/m±50 kA/m, due to the antiferromagnetism of Cr. TiC (15%) has no significant effect (magnetic permeability change <0.01±0.002).

Technology

Sintering temperature (1450°C±10°C) ensures the uniformity of Co phase (distribution error <5%±1%), and the magnetization intensity increases by 3%±0.5%; HIP (100 MPa±5 MPa) reduces defects (porosity <0.1%±0.02%), and increases by 2%±0.3%. Too high temperature (>1550°C) causes Co volatilization (loss <5%±1%), and decreases by 5%±1%.

Environment

High temperature (600°C) decreases by 20%±2% due to thermal vibration; damp heat (40°C, 90% humidity) decreases by <2%±0.5% due to Co corrosion; high pressure (>100 MPa) increases by 1%±0.3%; extreme cold (40°C) increases by 2%±0.3%; radiation (10^4 Gy) decreases by <1%±0.2%. Sample geometry: Thickness (>2 mm±0.1 mm) reduces the demagnetization effect (coefficient <0.9±0.1), up 2%±0.3%; surface roughness (Ra>0.4 μm) induces magnetic domain pinning, down 1%±0.2%.

Magnetic field conditions

High-frequency magnetic field (>10 kHz±0.1 kHz) induces eddy current loss (loss>1 W/cm³ ± 0.1 W/cm³) , which decreases by 2%±0.3%; magnetic properties are stable under static magnetic field.

For example, a fixture containing 6% Co and HIP process (1400 kA/m±50 kA/m) maintains a magnetization of 1350 kA/m±50 kA/m during high temperature processing (500°C), and the adsorption efficiency is >98%±1%. Optimization requires low Co and Ni substitution.

3.4.2.3 Magnetic saturation of cemented carbide

The magnetic saturation (Ms) of cemented carbide is a key parameter to measure the magnetization intensity when the cobalt binder phase reaches the maximum magnetization state under a strong magnetic field. It is measured in μTm³ / kg and directly reflects the cobalt content, microstructure state and integrity of carbon balance. As the core indicator of non-destructive testing of cemented carbide, magnetic saturation testing plays an irreplaceable role in quality control and performance optimization.

Technical principle

of the cobalt phase is completely aligned along the direction of the magnetic field under a sufficiently strong external magnetic field (usually >1.5 T), reaching the maximum magnetization intensity. At this point, the Ms value is mainly determined by the cobalt content and purity, because the hard phase (such as tungsten carbide WC) is a non-magnetic material and does not contribute to magnetism. The magnetic saturation intensity of pure cobalt is 16.1-16.3 μTm ³ /kg, and the Ms value in cemented carbide can be linearly estimated by the weight percentage of cobalt . For example, the theoretical Ms of YG8 alloy containing 8% cobalt is 1.29-1.30 μTm ³ /kg.

Ms and the theoretical value can be used to determine compositional anomalies or microscopic defects, such as the presence of η phase (Co_3W_3C) or free carbon (C). η phase will reduce Ms by 10-20%, and free carbon will reduce Ms by 5-10%. These changes provide a quantitative basis for defect detection.

Measurement method

Magnetic saturation testing is usually performed using a magnetic analyzer (such as Koerzimat 1.097 or Sigmameter 2.068) or a vibrating sample magnetometer (VSM). The test steps include the following:

Sample preparation

Select a cemented carbide sample (such as a tool blank, size 5-10 mm, cylinder or cube), clean the surface (use ethanol to remove oil and oxide layer), and weigh the mass (±0.01 g) to calculate the magnetization intensity per unit mass.

Magnetization process

The sample is placed in a strong magnetic field (1.5-2 T) and an electromagnetic saturation magnetization device is used to ensure that the cobalt phase is fully magnetized. The magnetic field strength must exceed the saturation magnetization threshold of cobalt to avoid under-magnetization leading to underestimation of Ms.

Data collection

Record the Ms value (μTm³ / kg) and infer the cobalt content through the formula Ms_alloy = Ms_pure cobalt × cobalt weight percentage (Ms_pure cobalt = 16.2 μTm³ / kg) . The measurement accuracy is controlled at ±0.5% and the repeatability is <2%.

Results Analysis

with the target Ms value, if the deviation is >±0.5% (such as the measured Ms of YG8 <1.23 μTm ³ /kg or >1.35 μTm ³ /kg), it indicates that there is a batching error or defect. If necessary, it can be verified by combining X-ray diffraction (XRD, detecting η phase 2θ≈40°) or metallographic analysis.

Influencing factors

The magnetic saturation of cemented carbide is affected by many factors, including:

Cobalt content

Ms is proportional to the cobalt content. When the cobalt content increases from 6% to 15%, Ms increases from 0.97 μTm ³ /kg (YG6) to 3.24 μTm ³ /kg (theoretical value). However, too high a cobalt content (>15%) may reduce the hardness (HRA drops from 91 to 89), so a trade-off in performance is required.

Carbon Balance

Imbalance in carbon content leads to η phase or free carbon. η phase causes Ms to decrease by 10-20% (e.g. YG8 from 1.29 to 1.0 μTm ³ /kg), and free carbon decreases by 5-10% (from 1.29 to 1.16 μTm ³ /kg), requiring adjustment of carbon content (6.0±0.2 wt %).

Microstructure

Grain size affects Ms stability. For fine-grained alloys (0.2-0.5 μm) , Ms fluctuates by less than 1%, while for coarse-grained alloys (>5 μm), Ms may fluctuate by 2-3% due to uneven grain boundaries.

Sintering process

High temperature (>1500°C) causes volatilization or oxidation of cobalt (Ms decreases by 5-8%), while low temperature and HIP (150 MPa, 1350°C) increase density (>99.5%) and Ms increases by 3-5%.

Environmental factors

High temperature (800-1000°C) reduces Ms by 5-10% (e.g. YG10 drops from 1.61 to 1.45 μTm ³ /kg at 1000°C), and damp heat (40°C, 90% humidity) reduces it by <2% due to Co microcorrosion.

Application Scenario

Magnetic saturation testing is widely used in the production and performance evaluation of cemented carbide:

Quality Control

Verify the cobalt content and carbon balance, such as YG6 (Ms = 0.97 μTm³ / kg) hardness HRA 90-91, YG8 (Ms = 1.29 μTm³ / kg) toughness KIC 10-12 MPa·m ¹ / ² .

Defect Detection

Ms <90% of the expected value (such as YG8 <1.16 μTm ³ /kg) indicates η phase, and >110% (>1.42 μTm ³ /kg) indicates free carbon, which guides formulation adjustment.

Performance prediction

Ms (deviation < ±0.3%) corresponds to high wear resistance (e.g. cutting life > 3 hours), while a fluctuation of Ms > 1% indicates a decrease in toughness (KIC < 8 MPa·m ¹ / ²).

Examples

In a deep-sea drill bit (pressure 50 MPa, temperature 40°C), the alloy containing 6% Co ensured hardness HRA 92 through Ms test (0.97 μTm ³ /kg) and life >300 hours, which is better than the untested drill bit (life <200 hours).

Data support

Benchmark value

Pure cobalt Ms =16.1-16.3 μTm ³ /kg, YG6 Ms =0.97 μTm ³ /kg, YG8 Ms =1.29 μTm ³ /kg, nano alloy (0.05-0.2 μm) Ms =1.1-1.3 μTm ³ /kg.

Defect Impact

The η phase reduces Ms by 10-20%, free carbon by 5-10%, and oxidation (1000°C) by 5-8%.

3.4.2.3 Coercive force of cemented carbide

The coercive force (Hc) of cemented carbide is an important parameter to measure the ability of the cobalt binder phase to resist demagnetization. It is measured in kA/m and directly reflects the grain size, microstructure distribution and sintering quality. The coercive force test plays a key role in the performance grading and application matching of cemented carbide, especially for the screening of high hardness and high toughness products.

Technical principle

Coercive force refers to the magnetic field strength required to apply a reverse magnetic field to reduce the magnetization intensity of the cobalt phase from the saturation state to zero. The Hc value is inversely proportional to the grain size of the cobalt phase . Fine grains (0.2-0.5 μm) have higher magnetocrystalline anisotropy, and Hc can reach 25-40 kA/m; while coarse grains (>5 μm) are easy to flip due to magnetization, and Hc is usually lower than 10 kA/m. In addition, Hc is also affected by the uniformity of cobalt phase distribution , defects (such as pores, η phase) and sintering process. High Hc of fine-grained structure corresponds to high hardness (HRA 89-92), and low Hc of coarse-grained structure corresponds to high toughness (KIC 15-20 MPa·m ¹ / ²), so Hc is an important indicator for microstructure optimization.

Measurement method

The coercivity test is usually performed using a permanent magnet coercivity meter or a magnetic analyzer. The specific steps are as follows:

Sample preparation

Select a cemented carbide sample (such as a mold blank, size 5-10 mm), clean the surface (remove oil and oxide layer), and ensure there is no magnetic interference.

Magnetization and demagnetization

The sample is first placed in a strong magnetic field (1.5-2 T) to be fully magnetized, and then a

gradually increasing reverse magnetic field is applied.

Data collection

Hc , kA/m) that makes the magnetization intensity drop to zero , and the measurement accuracy is controlled within ±1% and the repeatability is <2%.

Results Analysis

by the Hc value: >20 kA/m is a fine-grained structure, and <10 kA/m is a coarse- grained structure. If the Hc fluctuation is >10% (such as YG8 changes from 15 kA/m to 25 kA/m), it indicates uneven sintering or defects, and the grain boundaries need to be observed in combination with SEM (magnification 500x).

Influencing factors

The coercive force of cemented carbide is affected by a variety of factors, including:

Grain size

Hc is inversely proportional to the grain size. Fine-grained alloys (0.2 μm) have Hc = 30-40 kA/m, coarse-grained alloys (5 μm) have Hc = 5-10 kA/m. Nano-scale alloys (0.05-0.2 μm) have Hc up to 50-60 kA/m.

Cobalt content

Increasing the cobalt content (6% to 15%) makes the cobalt phase magnetization easier to flip and Hc decreases slightly (10-15%), but the effect is limited.

Carbon Balance

η phase reduces Hc by 5-10% (e.g. YG8 decreases from 15 to 13 kA/m), and the free carbon has little effect (<2%).

Sintering process

High temperature (>1500°C) leads to coarsening of grains and reduces Hc from 20 kA/m to 8 kA/m; HIP (150 MPa, 1350°C) improves uniformity and increases Hc by 5-10%.

Defects and stress

Porosity > 0.1% or residual stress (> 100 MPa) causes Hc to fluctuate by 10-15%, and density needs to be optimized (> 99.5%).

Environmental factors

High temperature (800°C) reduces Hc by 5-8% (e.g. YG10 drops from 18 to 16 kA/m), while damp heat (40°C, 90% humidity) affects <2%.

Application Scenario

Coercivity testing has diverse value in cemented carbide applications:

Performance classification

High Hc (>25 kA/m) is suitable for high hardness tools (such as PCB drill bits, HRA>92, life>4 hours); low Hc (<10 kA/m) is suitable for high toughness molds (such as mining drill bits, KIC>15 MPa·m $^{1/2}$, life>200 hours).

Process Optimization

Hc (fluctuation > 10%) indicates coarse grains or uneven sintering, guiding temperature adjustment (1350-1450°C) or adding grain inhibitors (such as VC 0.2-0.5 wt %).

Defect Detection

in Hc (e.g., from 15 to 13 kA/m for YG8) may be due to the η phase, which requires adjustment of the carbon content (6.0 ± 0.2 wt %).

Examples

In automotive steel sheet stamping (load > 2000 MPa, frequency > 10^4 times/hour), dies containing 8% Co ensure hardness HRA 90 and fracture rate < 0.5% through Hc test (15 kA/m), and life > 6000 hours.

Data support

Benchmark value

YG6 Hc =15-20 kA/m, YG8 Hc =10-15 kA/m, nano alloy Hc =50-60 kA/m.

Defect Impact

η phase reduces Hc by 5-10%, porosity 0.1% reduces Hc by 10-15%, and high temperature (800°C) reduces it by 5-8%.

3.5 Summary and Outlook

Cemented carbide (hardness HV 15002500±30, toughness K_{1c} 820 MPa·m$^{1/2}$ ± 0.5 , compressive/flexural strength>4000 MPa±100 MPa, thermal conductivity 80120 W/m·K±5 W/m·K , thermal expansion coefficient 46×10^{-6} / K± 0.1×10^{-6} /K, high temperature stability>1000°C, corrosion resistance pH 212, resistivity 20 μΩ·cm±5 μΩ·cm , Co phase magnetization 1400 kA/m±50 kA/m) are derived from the synergistic effect of WC rigidity, Co/Ni plasticity and additives (TiC , TaC , Cr, Mo). This chapter comprehensively reveals its performance mechanism and regulation method by refining the characteristic description, inspection and detection methods, influencing factors and application cases.

Mechanical properties (hardness, toughness, compressive/flexural strength) support cutting, mining, stamping, aviation and deep-sea drilling. Optimization requires low Co (6%8%), TaC /Cr addition and HIP process.

Thermal properties (thermal conductivity, thermal expansion coefficient, high temperature stability,

thermal shock resistance) ensure high temperature cutting, aero-engine and nuclear power applications, and optimization requires TiC addition , Al_2O_3 / TiN coating and uniform sintering.

Chemical stability (corrosion resistance , oxidation resistance) ensures service in chemical, marine and high temperature environments. Optimization requires Ni/Cr/Mo addition and CrN / Al_2O_3 coating .

The electrical and magnetic properties (conductivity, magnetism) support EDM, magnetic detection and aerospace sensors, and optimize the process of replacing Co with Ni and high density.

Environmental factors (high temperature 6001000°C, wet heat 40°C/90%, high pressure>100 MPa, extreme cold 40°C, radiation 10 ⁴ Gy) and process conditions (sintering 1450°C±10°C, HIP 100 MPa±5 MPa) have a significant impact on performance, and the composition and process need to be adjusted according to the working conditions. For example, the tool containing 8% Co and Al ₂ O ₃ coating has a life of >12 hours±1 hour in aviation cutting (1000°C), the valve containing NiCr can operate for 5 years in the deep sea (5000 m), and the sensor containing 12% Ni has a signal error of <0.1%±0.02% in aerospace (500°C).

Performance regulation of nano-additives (such as VC, <0.5%), multi-layer coatings (such as TiN/Al_2O_3 / TiCN , < 10 μm ± 1 μm) and extreme environments (>1500°C, >500 MPa, pH<1), and combine machine learning to predict the relationship between composition, process and performance to enhance the competitiveness of cemented carbide in the fields of energy, aerospace and nuclear power. This chapter is connected with Chapter 2 (hypothetical microstructure) through the contribution of WCCo , laying the foundation for subsequent process optimization (Chapter 4) and application expansion (Chapter 5).

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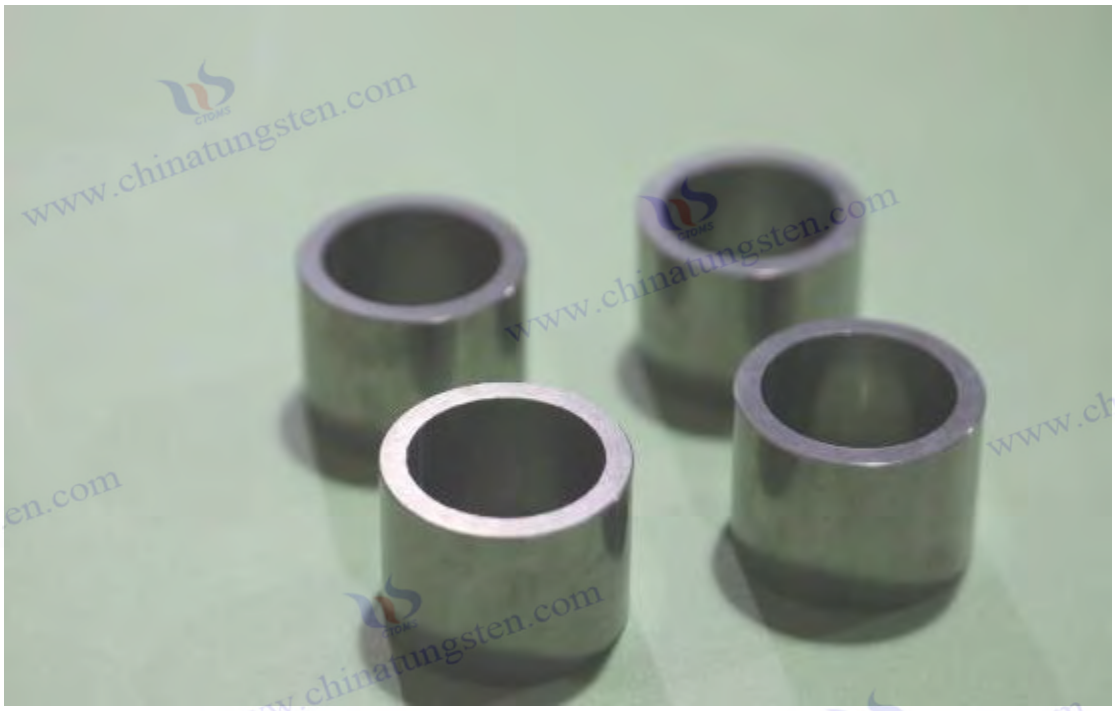

Appendix:

Cemented Carbide Cobalt Magnets: Definition and Test Methods

1. Introduction

Cemented carbide (such as tungsten carbide-cobalt alloy, WC-Co) occupies an important position in the industrial field due to its excellent high hardness (Vickers hardness HV 1200-2400), wear resistance (wear rate <0.1 $mm^3 / N \cdot m$) and toughness (fracture toughness KIC 8-20 $MPa \cdot m^{1/2}$) , and is widely used in cutting tools, drill bits, molds, mining tools and other scenarios. Cobalt (Co), as a binding phase in cemented carbide, not only enhances the material's impact resistance and fracture toughness through its plastic deformation ability, but also gives cemented carbide a quantifiable magnetic property called "Cobalt Magnetism" due to its unique ferromagnetism. Cobalt magnetism can non-destructively evaluate cobalt content, carbon balance state, microstructural integrity and process quality by measuring parameters such as magnetic saturation intensity (Ms) and coercive force (Hc) , and is an indispensable quality control method in cemented carbide production. This article will systematically explain the definition and testing methods of cobalt magnets , as well as their far-reaching significance for cemented carbide performance and production optimization. At the same time, it will explore methods to improve cobalt magnet testing and application to further enhance the performance and reliability of cemented carbide.

2. Definition of cobalt magnetism in cemented carbide

2.1 The meaning and physical basis of cobalt magnetism

In cemented carbide, cobalt magnetism refers to the magnetic properties exhibited by the cobalt

binder phase, which is mainly characterized by two key parameters: magnetic saturation intensity (Ms) and coercive force (Hc). Magnetic saturation intensity (Ms) refers to the magnetization intensity when the cobalt phase reaches full magnetization under the action of a strong magnetic field (>1.5 T) , and the unit is μTm³ /kg (magnetic moment per kilogram of material). The Ms value is proportional to the cobalt content and purity. The magnetic saturation intensity of pure cobalt is 16.1-16.3 μTm³ / kg. Therefore, the Ms value of cemented carbide can be linearly estimated by the cobalt content. For example, the theoretical Ms of an alloy containing 10% cobalt is about 1.61-1.63 μTm³ / kg. Coercive force (Hc) refers to the reverse magnetic field intensity required to reduce the magnetization intensity of the cobalt phase from the saturation state to zero, and the unit is kA/m (kiloamperes /meter). Hc is closely related to the grain size and microstructural distribution of the cobalt phase . Fine grains (0.2-0.5 μm) usually exhibit high coercivity (>25 kA/m), while coarse grains (>5 μm) have lower coercivity (<10 kA/m).

The magnetism of cemented carbide comes almost entirely from the cobalt binder phase, because the hard phase (such as WC) is a non-magnetic material. Cobalt's high magnetization intensity (1.7-1.75 μB /atom) and high Curie temperature (about 1145°C) make it an ideal indicator for magnetic measurement. The cobalt content is usually between 5-15 wt %, and its magnetic properties not only reflect the distribution and state of the cobalt phase , but also indirectly characterize the composition uniformity and microstructural integrity of the cemented carbide, providing a reliable means for non-destructive testing.

2.2 The significance of cobalt magnets to cemented carbide

Cobalt magnetic testing has far-reaching significance in many aspects of cemented carbide production and application. It is not only a core tool for quality control, but also provides an important basis for process optimization and performance prediction.

First of all, the cobalt magnetic test can accurately verify whether the cobalt content meets the requirements of the formula design. The magnetic saturation intensity (Ms) is linearly related to the cobalt content. For example, the theoretical Ms of YG6 (6% cobalt) alloy is 0.97 μTm³ / kg, and that of YG8 (8% cobalt) is 1.29 μTm³ / kg. If the measured Ms deviation exceeds ±0.5%, there may be a problem of insufficient or excessive cobalt content, which directly affects the hardness and toughness balance of cemented carbide. Insufficient cobalt content will lead to insufficient bonding phase, decreased alloy toughness (KIC may drop from 12 MPa·m $^{1/2}$ to 8 MPa·m $^{1/2}$), and increased risk of tool chipping ; excessive cobalt content will reduce hardness (HRA drops from 91 to 89), affecting wear resistance. Through cobalt magnetic testing, the ingredient ratio can be quickly adjusted to ensure that the cobalt content is accurately controlled within the target range.

Secondly, cobalt magnetic testing is an effective means to evaluate the carbon balance state. Imbalance in the carbon content of cemented carbide will lead to the formation of η phase (Co_3W_3C) or free carbon (C), and these defects have a significant negative impact on performance. η phase is a brittle phase that will reduce Ms by 10-20% and reduce toughness (KIC decreases by 15-

20%), causing the tool to break easily under high impact conditions (such as mining drilling, frequency>2000 times/minute). Free carbon reduces Ms by 5-10% and reduces hardness (HV decreases by 50-80), affecting wear resistance (wear rate increases from 0.05 to 0.07 $mm^3/N \cdot m$). Through cobalt magnetic testing, if Ms is lower than 90% of the expected value (such as YG8 measured Ms <1.16 $\mu Tm^3/kg$), η phase may be present; if it is higher than 110% (>1.42 $\mu Tm^3/kg$), free carbon may be present. At this point, X-ray diffraction (XRD) can be combined to further confirm the defect type and eliminate the defect by adjusting the carbon content (target 6.0±0.2 wt %) or optimizing the sintering process (increasing the temperature to 1350-1450°C).

In addition, the cobalt magnetic test can also reflect the characteristics of the microstructure and the process quality. The coercive force (Hc) is inversely proportional to the cobalt phase grain size. Fine-grained cemented carbide (grains 0.2-0.5 μm) Hc is usually 25-40 kA/m, which is suitable for high-hardness tools (such as PCB drill bits, HRA>92); coarse-grained cemented carbide (grains>5 μm) Hc is 5-10 kA/m, which is suitable for high-toughness applications (such as mining drill bits, KIC>15 $MPa \cdot m^{1/2}$). Abnormal Hc fluctuations (>10%) may indicate uneven sintering or abnormal grain growth, and the sintering temperature (controlled at 1350-1450°C) or holding time (1-2 hours) needs to be adjusted. Through cobalt magnetic testing, the microstructure design can be optimized to ensure the best balance between hardness and toughness.

More importantly, cobalt magnetic testing provides a direct basis for performance prediction and process improvement. High Ms and high Hc usually correspond to high hardness and wear resistance, which are suitable for high-speed cutting tools; low Hc corresponds to high toughness and impact resistance, which are suitable for mining tools. For example, in the cutting of aviation titanium alloys (cutting speed 200 m/min), a tool containing 10% cobalt can pass the cobalt magnetic test (Ms = 1.61 $\mu Tm^3/kg$, Hc = 18 kA/m) to ensure hardness HRA 90 and impact resistance, and the tool life is 3-4 hours, which is better than the untested tool (life < 2 hours). In addition, cobalt magnetic testing can also guide the optimization of sintering process to avoid overburning (temperature > 1500°C, coarse grains, Hc decrease) or underburning (temperature < 1300°C, η phase formation, Ms decrease), thereby improving production consistency and product reliability.

3. Cobalt magnetic test method

Cobalt magnetic testing evaluates the performance of cemented carbide by measuring magnetic saturation intensity (Ms) and coercivity (Hc). It is a non-destructive testing method that is easy to operate and has reliable results. The following is a detailed description of the test principle, equipment, steps, standards and precautions.

3.1 Test Principles and Technical Basis

cobalt magnetic testing is to utilize the ferromagnetic properties of cobalt and quantify its state through magnetic saturation intensity and coercivity. The measurement of magnetic saturation intensity (Ms) is based on the complete magnetization of the cobalt phase under a strong magnetic

field (>1.5 T) . Its value is proportional to the cobalt content and is calculated as follows: Ms_alloy = Ms_pure cobalt × cobalt weight percentage, where the Ms of pure cobalt is 16.1-16.3 μTm³ / kg. For example, the theoretical Ms of an alloy containing 8% cobalt is 1.29-1.30 μTm³ / kg. If the measured value deviates, the composition or defect cause needs to be analyzed. Coercivity (Hc) measures the intensity at which the reverse magnetic field reduces the magnetization intensity to zero, which is inversely proportional to the cobalt grain size . The Hc of fine-grained alloys (0.2 μm) can reach 30-40 kA/m, and the Hc of coarse-grained alloys (5 μm) drops to 5-10 kA/m. Defects such as η phase or free carbon can significantly affect Ms. η phase reduces Ms by 10-20% and free carbon reduces Ms by 5-10%. These changes can be used to quickly troubleshoot material problems.

3.2 Test equipment and its performance

Cobalt magnetic testing relies on professional equipment to ensure measurement accuracy and reliability. Commonly used equipment includes magnetic analyzers (such as Koerzimat 1.097 or Sigmameter 2.068), which can measure Ms and Hc simultaneously with an accuracy of ±0.5%, suitable for factory batch testing. The vibrating sample magnetometer (VSM) provides higher accuracy (±0.1 μTm ³ /kg), can measure the complete hysteresis loop, and is suitable for laboratory research on microscopic magnetic properties. The permanent magnet coercivity meter is suitable for rapid measurement of Hc (accuracy ±1 kA/m), easy to operate, and often used for on-site testing. The electromagnetic saturation magnetization device ensures that the cobalt phase is fully saturated by applying a strong magnetic field of 1.5-2 T, with a measurement error of <1%, and is the core tool for Ms testing.

3.3 Test steps and operation flow

Cobalt magnetic testing must be performed following standardized procedures to ensure accurate and repeatable results.

Sample preparation

Select a carbide sample (such as a tool blank, size 5-10 mm, cylindrical or cubic), clean the surface, remove oil and oxide layer (can be wiped with ethanol) to avoid interference with magnetic measurement. Accurately weigh the sample mass (±0.01 g) to calculate the unit mass magnetization intensity.

Magnetic saturation test

Place the sample in a strong magnetic field (1.5-2 T) of a magnetic analyzer to fully magnetize the cobalt phase and record Ms (μTm³ / kg). Calculate the cobalt content using the formula Ms ÷ 16.1 and compare it with the target value. A deviation of >±0.5% indicates abnormal or defective ingredients.

Coercivity test

Use a coercivity meter to apply a reverse magnetic field and measure Hc (kA/m) that reduces

magnetization to zero. Determine the grain size based on the Hc value: >20 kA/m is a fine-grained structure, suitable for high-hardness tools; <10 kA/m is a coarse- grained structure, suitable for high-toughness molds.

Data analysis

Analyze the results of Ms and Hc . If Ms is too low (<90% of the expected value), there may be insufficient cobalt or η phase. If Ms is too high (>110%), there may be free carbon. Abnormal fluctuation of Hc (>10%) indicates uneven sintering. If necessary, further verification can be performed by combining metallographic microscope (magnification 200x) or XRD (detection of η phase 2θ≈40°, free carbon 2θ≈26°).

Result recording and processing: record Ms , Hc and sample number and store them in the quality database. Abnormal results require adjusting the recipe (such as adding 0.1-0.2% carbon) or optimizing the sintering process (adjusting the temperature by ±10°C and extending the holding time to 1.5 hours).

3.4 Test standards and specifications

Cobalt magnetic testing must follow international and domestic standards to ensure the reliability of the results. ISO 3326:2013 specifies the method for determining the magnetic saturation of cemented carbide cobalt , clearly defining the equipment calibration (using pure cobalt standards), sample size (5-10 mm) and accuracy requirements (±0.5%).

ASTM B886 is a general standard for testing the magnetic properties of cemented carbide, covering Ms and Hc measurements, and emphasizing test environment control (20-25°C, no magnetic interference). China's national standard GB/T 3849 further requires test repeatability (deviation <2%) and equipment calibration cycle (once a month) to ensure production consistency.

3.5 Precautions and Error Control

To ensure the accuracy of the test, the following points should be noted: the equipment needs to be calibrated regularly, using pure cobalt (Ms = 16.2 μTm³ / kg, Hc = 5 kA/m) or standard samples, and the error is controlled within ±1%. The sample must be uniform, free of cracks (<5 μm), pores (<0.05%), and the composition deviation is <0.1 wt %, otherwise it may cause measurement deviation. The test environment should be free of strong magnetic field interference (<0.1 mT), the temperature should be controlled at 20-25°C, and the humidity should be <60%. If the result is abnormal (Ms deviation > 5%, Hc fluctuation > 10%), it is necessary to combine chemical analysis (such as ICP measurement of cobalt content, accuracy ±0.05 wt %) or scanning electron microscopy (SEM) to observe microscopic defects (such as pores, η phase distribution) for comprehensive verification.

4. Optimization and improvement methods of cobalt magnetic testing

In order to further improve the accuracy and application value of cobalt magnetic testing, improvements can be made in three aspects: equipment improvement, process optimization and data analysis. The specific methods are as follows.

In terms of equipment improvement, the use of higher-precision testing instruments is the key to improving the cobalt magnetic testing results. With the widespread application of nano-scale cemented carbide (grain size 0.05-0.2 μm), its high coercivity (Hc >50 kA/m) and complex microstructure have put forward higher requirements for testing accuracy. The accuracy (±0.5%) of traditional magnetic analyzers (such as Koerzimat) can no longer meet the needs. It is recommended to introduce a high-precision vibrating sample magnetometer (VSM, accuracy ±0.1 μTm ^{3} /kg), which can more accurately measure the hysteresis loop and microscopic magnetic changes. In addition, the development of high-temperature cobalt magnetic testing equipment (supporting 800-1000°C testing) can evaluate the attenuation characteristics of cobalt magnetism under high temperature conditions (Ms decreases by 5-10%), providing performance prediction support for high-temperature tools (such as aviation engine processing tools). For example, at 1000°C, the Ms of cemented carbide containing 10% cobalt dropped from 1.61 to 1.45 μTm^3 / kg, indicating high-temperature oxidation or cobalt volatilization. The coating (such as TiAlN , thickness 2-3 μm) needs to be optimized to improve heat resistance.

In terms of process optimization, defects such as η phase and free carbon can be reduced by improving the sintering process and formula design, thereby improving the stability of cobalt magnetic test results . The sintering temperature should be strictly controlled at 1350-1450°C. Too high temperature (>1500°C) will lead to coarse grains (Hc drops from 20 kA/m to 8 kA/m), and too low temperature (<1300°C) will easily form η phase (Ms drops to <90% of the expected value). The hot isostatic pressing (HIP, 150-200 MPa, 1350°C) process can effectively reduce porosity (from 0.1% to 0.05%), improve Ms value (increase 3-5%) and Hc stability (fluctuation <5%). In addition, adding trace grain inhibitors (such as VC 0.2-0.5 wt % or Cr_3C_2 0.3-0.8 wt %) can control the cobalt phase grain size (0.5-1 μm), increase Hc (from 15 kA/m to 20-25 kA/m), and reduce the formation of η phase (Ms is restored to 98% of the expected value). In terms of formulation design, optimizing the carbon content (6.0±0.2 wt %) and cobalt content (6-10 wt %) can avoid free carbon and η phase, and the Ms deviation is controlled within ±0.3%. For example, after HIP and VC addition of cemented carbide containing 8% cobalt, Ms is stabilized at 1.28-1.30 μTm ^{3} /kg, and the tool life is increased by 20% (from 3 hours to 3.6 hours).

In terms of data analysis, the introduction of intelligent analysis technology can significantly improve the efficiency and accuracy of cobalt magnetic testing. In 2025, artificial intelligence (AI) and machine learning (ML) have been widely used in cobalt magnetic data analysis . By building an Ms-Hc -performance database, AI can predict defect types and performance impacts. For example, if Ms <1.16 μTm ^{3} /kg (YG8 standard 1.29 μTm ^{3} /kg), AI can automatically prompt the possibility of η phase (probability>80%) and recommend adjusting the carbon content (+0.1-0.2

wt %) or reburning (1350°C, 1.5 hours). In addition, the real-time monitoring system (combined with infrared spectroscopy to monitor the sintering atmosphere) can dynamically adjust the sintering parameters to ensure the consistency of Ms and Hc (deviation <2%). Intelligent analysis also supports cross-condition performance prediction. For example, in a hot and humid environment (40°C, 90% humidity), the Ms stability of Ni-Co (Ni 5-10%) alloys is improved by 5-10%, which is suitable for marine engineering applications (lifetime>3 years).

The actual effect of the comprehensive improvement method is remarkable. For example, a tool manufacturer optimized the cobalt magnetic test (VSM+AI analysis) to control the Ms deviation to ±0.2%, Hc fluctuation <3%, and η phase ratio to <1%, and the tool hardness (HRA 91-92) and life (cutting titanium alloy, 200 m/min) increased by 25% (from 3 hours to 3.75 hours). Similar improvements in mining drill bits (impact frequency>2000 times/minute) extended the life by 30% (from 200 hours to 260 hours), fully verifying the application value of cobalt magnetic test optimization.

5. Application scenarios of cobalt magnetic testing

Cobalt magnetic testing has extensive practical value in cemented carbide production and applications.

Quality Control

By verifying the cobalt content and carbon balance, we can ensure that the carbide performance meets the standards. For example, YG6 (6% cobalt, Ms =0.97 μTm ^{3} /kg, Hc =15-20 kA/m) has a tool hardness of HRA 90-91 and a toughness of KIC 10-12 MPa·m $^{1/2}$, which is suitable for general cutting.

Process Optimization

Guide the adjustment of sintering process to avoid coarse grains (Hc <8 kA/m) or η phase formation (Ms <0.9 μTm ^{3} /kg) and improve product consistency.

Defect Detection

Identify η phase or free carbon to guide formulation adjustments (such as adding 0.1-0.2% carbon) to reduce toughness loss (KIC decreases by 15%) or hardness loss (HV decreases by 50-80).

Performance prediction

High Hc (>25 kA/m) is suitable for high hardness tools (such as PCB drill bits, life>4 hours); low Hc (<10 kA/m) is suitable for high toughness molds (such as mining drill bits, life>200 hours).

Examples

In the cutting of aviation titanium alloy (200 m/min), the tool containing 10% cobalt passed the cobalt magnetic test (Ms = 1.61 μTm ^{3} /kg, Hc = 18 kA/m) to ensure hardness and impact resistance, and the life span reached 3-4 hours, which is better than the untested tool (life < 2 hours).

6. Data support and latest progress

Magnetic performance benchmark:

Pure cobalt: Ms =16.1-16.3 μTm ³ /kg, Hc =5-6 kA/m, Curie temperature 1145°C.

YG6 (6% cobalt): Ms =0.97 μTm³ / kg , Hc =15-20 kA/m.

YG8 (8% cobalt): Ms =1.29 μTm ³ /kg, Hc =10-15 kA/m.

Nanoscale alloys (0.05-0.2 μm): Hc =50-60 kA/m, Ms =1.1-1.3 μTm³ / kg (grain boundary effect).

Defect impact:

η phase: Ms decreases by 10-20%, such as YG8 decreases from 1.29 to 1.0 μTm ³ /kg.

Free carbon: Ms decreases by 5-10%, such as YG6 decreases from 0.97 to 0.87 μTm ³ /kg.

Grain size 1-2 μm : Hc =10-15 kA/m, best hardness-toughness.

Progress by 2025:

Nano-grade cemented carbide production has increased to 20% of the world's total, and the demand for high Hc (>50 kA/m) has promoted the popularization of VSM (accuracy ±0.05 μTm ³ /kg). The Ms stability of Ni-Co alloys (Ni 5-10%) in marine environments (salinity 3.5%, 50 MPa) has increased by 5-10%, and the application proportion has reached 15%. AI analysis has increased the defect detection rate by 20%, and Ms abnormalities have automatically triggered SEM analysis.

7. Conclusion

in cemented carbide is the magnetic property of the cobalt binder phase. It reflects the cobalt content, carbon balance and microstructure through magnetic saturation intensity (Ms) and coercivity (Hc), and is a core tool for quality control and performance optimization. Cobalt magnetic testing can not only verify the composition and troubleshoot defects, but also guide process optimization and performance prediction, which is of great significance to improving the hardness, toughness and wear resistance of cemented carbide. By introducing high-precision equipment (such as VSM), optimizing sintering process (HIP+grain inhibitor) and intelligent data analysis (AI+real-time monitoring), the accuracy and application value of cobalt magnetic testing have been significantly improved, providing strong technical support for the high-performance application of cemented carbide.

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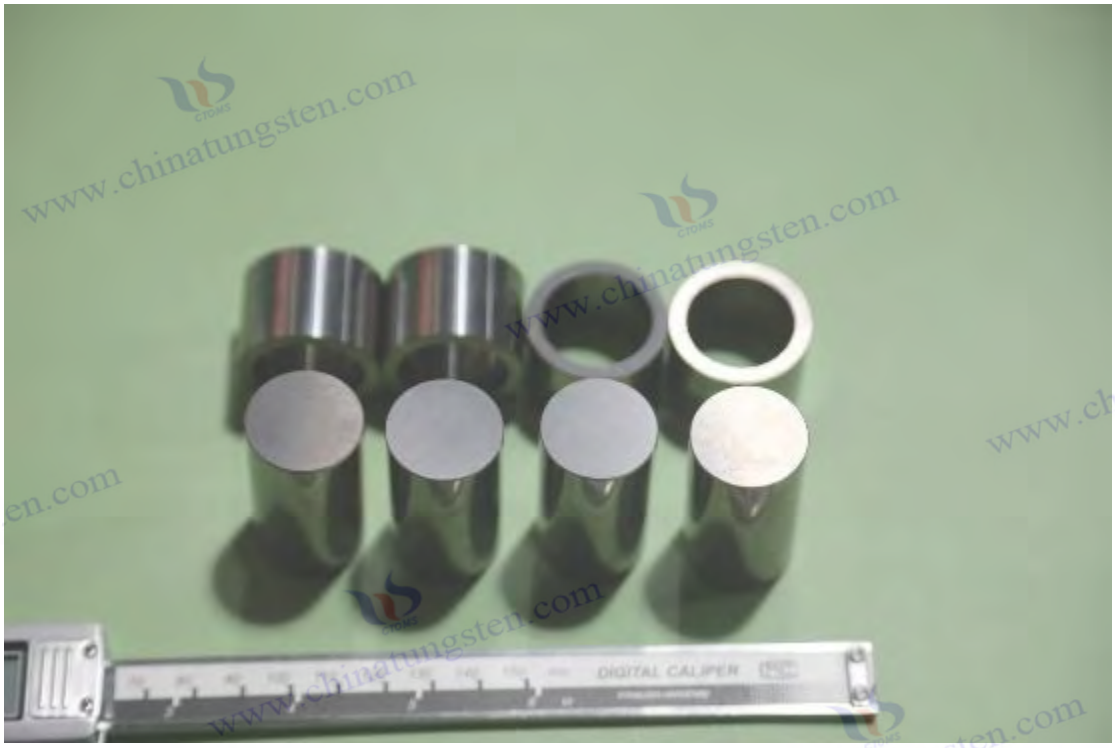

Appendix:

ISO 3326:2013 Method for determination of magnetic saturation of cobalt in cemented carbide

ISO 3326:2013 Hardmetals —

Determination of Mechanical Saturation of Carbon Published: July 2013

Status: Currently valid Scope of application: This standard specifies the method for determining the magnetic saturation intensity of cobalt (Co) in cemented carbide. It is applicable to cemented carbide containing at least 3% (mass fraction) ferromagnetic binder (mainly cobalt) for quality control and composition analysis.

1. Scope

This standard describes a non-destructive method for determining the magnetic saturation (Ms) of cobalt in cemented carbides to assess the cobalt content, carbon balance and alloy quality.
WCCo alloys) containing ferromagnetic binders (such as cobalt and nickel, with a mass fraction of ≥3%) , but not suitable for non-magnetic or low-magnetic alloys.
The test results are used to:
Verify that the cobalt content is within specification.
Detects carbon content imbalances (such as eta phase or free carbon).
Evaluation of the sintering process quality (e.g. presence of non-magnetic inclusions).

2. Normative References

There are no direct references to other standards, but it is recommended to refer to relevant cemented

carbide testing standards, such as:
ISO 4499 (Determination of microstructure of cemented carbides).
ISO 3738 (Methods for sampling of cemented carbides).
It is highly relevant to the content of ASTM B886 (Magnetic Saturation Test of Cemented Carbide) and can be used as a supplementary reference.

3. Terms and Definitions

Hardmetal : A composite material consisting of a hard phase (such as tungsten carbide WC) and a bonding phase (such as cobalt).
Magnetic Saturation (Ms): The intensity at which the magnetization of the cobalt phase reaches its maximum value under a strong magnetic field , with the unit of μTm^3 /kg or $kA \cdot m^2$ / kg.
Ferromagnetic Binder: Cobalt, nickel and other metal phases with ferromagnetism, with cobalt being the most common.
η Phase (Eta Phase): Brittle carbides (such as Co3W3C) formed when there is insufficient carbon , which reduces magnetism and toughness.
Free Carbon: Non-magnetic carbon that precipitates when there is excess carbon, weakening the strength of the alloy.

4. Principle

The magnetism of cemented carbide comes from the cobalt binder phase, and the hard phase (such as WC) does not contribute to magnetism.
Under strong magnetic fields (usually >1.5 T), the cobalt phase reaches magnetic saturation, and Ms is proportional to the cobalt content. The magnetic saturation constant of pure cobalt is 16.116.3 μTm^3 / kg (ScienceDirect, 2020).
Ms measurement can:
Calculate the cobalt content: Ms ÷ 16.1 μTm^3 /kg ≈ Cobalt mass fraction.
Detection of non- magnetic impurities: η phase or oxides reduce Ms (1020%), free carbon reduces Ms (510%).
The test is non-destructive and independent of sample shape and size (within certain limits).

5. Apparatus

Magnetic analyzer: such as Koerzimat MS or Sigmameter , equipped with a strong magnetic field generator (1.52 T) and a magnetic flux detection system.
Calibration standard sample: pure cobalt or cemented carbide sample with known cobalt content, Ms value traceable to SI unit.
Precision balance: accuracy ±0.01 g, used to weigh the sample mass.
Constant temperature device: The test environment temperature is controlled at 2025°C to avoid thermal effects.
Demagnetization equipment (optional): Ensures that the sample has no residual magnetization.

6. Test Specimen

Shape and size: The sample can be any shape (such as cylinder, cube, tool blank), the size is usually 510 mm and the mass is 0.550 g.
Surface requirements: clean, free of oil, oxide layer or mechanical damage.
Homogeneity: The internal composition of the sample is uniform, with no obvious cracks or pores.
Quantity: At least 3 samples per batch, representative sampling according to ISO 3738.

7. Test steps (Procedure)

Equipment Calibration:
using pure cobalt standards (Ms = 16.1 μTm³ / kg) or certified carbide samples.
The calibration error is controlled within ±1% and the calibration data is recorded.
Sample preparation:
Clean the sample surface to remove oil, dirt and oxides.
Weigh the sample mass (m, unit: g) using a precision balance with an accuracy of ±0.01 g.
If the sample has residual magnetization, use demagnetization equipment.
Magnetic saturation measurement:
Place the sample in a strong magnetic field (1.52 T) of a magnetic analyzer to ensure that the cobalt phase is fully magnetized.
Measure the magnetic flux and record the magnetic saturation intensity (Ms , in μTm³ / kg).
The measurement was repeated 3 times and the average value was taken. The deviation of a single measurement was <±0.5%.
Data Records:
Record the sample number, mass, Ms value and test conditions (temperature, magnetic field strength).
If Ms is abnormal, check the sample or equipment and retest if necessary.

8. Calculation and Expression of Results

cobalt content:

$$\text{钴质量分数}(\%) = \frac{Ms}{Ms_{\text{纯钴}}} \times 100$$

Among them, Ms is the measured value, Ms pure cobalt is 16.1 μTm ³ /kg. For example, Ms =1.61 μTm ³ /kg, the cobalt content ≈10%.
Relative magnetic saturation (S):

$$S = \frac{Ms_{\text{测量}}}{Ms_{\text{理论}}}$$

Ms theory is the magnetic saturation value (based on the cobalt content) of a hypothetical pure cobalt binder phase. S < 0.9 indicates η phase, and S > 1.1 indicates free carbon.

Precision: The result is retained to 3 decimal places (e.g. 1.610 μTm³ / kg), and the cobalt content is retained to 1 decimal place (e.g. 10.0%).

9. Test results analysis

Normal range: The magnetic saturation value of cobalt after sintering is usually 85-95% of the theoretical value (because part of the cobalt dissolves into WC or forms a non-magnetic phase).
Abnormal situation:
Ms is low (<90%): η phase (Co3W3C), oxide or insufficient cobalt content may exist.
Ms is too high (>110%): There may be excessive free carbon or cobalt content.
Supplementary verification: Abnormal results need to be combined with metallographic analysis (microscope observation of η phase, free carbon) or chemical analysis (ICP measurement of cobalt content).

10. Test Report

The report should include the following:
Standard reference: ISO 3326:2013.
Sample information: number, shape, quality, batch.
Test conditions: device model, magnetic field strength (T), ambient temperature (°C).
Results: Ms value (μTm³ / kg), calculated cobalt content (%), relative magnetic saturation (S).
Calibration information: Ms value of standard sample, calibration date.
Exception description: If there is a deviation, describe the possible cause (such as η phase).
Tester: Name, date, signature.
Laboratory information: name, address, certification qualifications.

11. Precautions

Equipment calibration: Regular calibration, error <±1%, using traceable standard samples.
Sample uniformity: Avoid cracks, pores or uneven composition that affect Ms accuracy.
Environmental control: The test environment has no strong magnetic field interference and the temperature is 2025°C.
Safety: Comply with equipment operating procedures to avoid the impact of strong magnetic fields on personnel or electronic equipment.
Data verification: Abnormal Ms values need to be tested repeatedly and confirmed in combination with metallographic or XRD analysis.

12. Annexes

Appendix A (informative): Relationship between cobalt magnetic saturation and carbon content.
Ms range of typical WCCo alloys is provided (e.g. YG6: Ms≈0.97 μTm³ / kg, YG8: Ms≈1.29 μTm³ / kg).

The chart shows the effect of η phase and free carbon on Ms (η phase decreases by 1020%, free carbon decreases by 510%).

Appendix B (informative): Equipment calibration guide.

Recommended calibration frequency (monthly or every 1000 tests), standard sample requirements.

Appendix C (informative): Error source analysis.

Sample inhomogeneity, uncalibrated equipment, environmental magnetic field interference, etc.

13. Links to related standards

ASTM B886: Similar method for determining magnetic saturation of cemented carbide, emphasizing non-destructiveness and indirect assessment of carbon content (ASTM B886, 2024).

Appendix:

Cemented carbide magnetic saturation test method: ASTM B88624

1. Introduction

Cemented carbide (such as tungsten carbide cobalt alloy, WCCo) is widely used in industrial fields such as cutting tools, molds, and drills due to its high hardness, wear resistance, and toughness. **Magnetic saturation strength (Ms)** is a key indicator for evaluating the content and quality of ferromagnetic binding phases (such as cobalt and nickel) in cemented carbide. The ASTM B88624 standard specifies the method for determining the Ms of cemented carbide powders and sintered products using a magnetic saturation tester, which is suitable for non-destructive quality control, indirect evaluation of carbon content, and product acceptance. This article introduces the content of ASTM B88624 in detail, including the scope, principles, equipment, procedures, calculations, and reporting requirements, to provide a reference for practitioners.

2. Standard scope

This standard describes a non-destructive test method to determine the magnetic saturation intensity (Ms) in cemented carbide powders and sintered products to evaluate the magnetic fraction of ferromagnetic binding phases (such as cobalt, nickel, iron). Applicable objects include:
Cemented carbide powder before sintering.
Sintered products such as knives, molds, drills.
Purpose of the test:
Indirect assessment of carbon content, detection of η phase (Co3W3C) or free carbon.
Verify binder phase content to ensure specifications are met.
Evaluate powder and sintered product quality for product acceptance.
The standard is based on SI units (μTm³ / kg) and supplemented by inch- pound units.

3. Terms and Definitions

Cemented carbide : A composite material composed of a hard phase (such as tungsten carbide WC, titanium carbide TiC) and a ferromagnetic bonding phase (such as cobalt, nickel).
Magnetic saturation intensity (Ms) : The intensity at which the magnetization of the binding phase reaches its maximum value under a strong magnetic field, with the unit of μTm³ / kg, reflecting the cobalt or nickel content.
Ferromagnetic binder phase : cobalt (Co), nickel (Ni) or iron (Fe), provides magnetism and toughness, with cobalt being the most common .
η phase : Non-magnetic carbide (such as Co3W3C) formed when carbon is insufficient , which reduces Ms and toughness.
Free carbon : non-magnetic carbon precipitated when carbon is excessive, reducing Ms and strength.
Magnetic saturation constant : pure cobalt Ms is 16.116.3 μTm ³ /kg, nickel is 5.4 μTm ³ /kg.

4. Significance and Use

Non-destructive : No need to destroy the sample, suitable for powder and sintered products.
Carbon content assessment : Ms reflects carbon balance, η phase or free carbon decreases Ms.
Quality control : verification of cobalt/nickel content, detection of sintering defects (e.g. oxides).
Product acceptance : Ensure that the product meets grade specifications (such as YG6, YG8).
Limitations : Only applicable to cemented carbides containing ferromagnetic binder phase, not applicable to non-magnetic alloys.

5. Test Principle

The magnetism of cemented carbide comes from the ferromagnetic binder phase (such as cobalt), and the hard phase (such as WC) does not contribute to magnetism. Under a strong magnetic field (1.52 T), the binder phase reaches magnetic saturation, and Ms is proportional to the binder phase content. The formula for calculating the cobalt content is Ms ÷ 16.1 μTm ³ /kg ≈ Cobalt mass fraction. For example, Ms = 1.61 μTm³ / kg means the cobalt content is about 10%. Non-magnetic impurities (such as η phase, free carbon, oxides) reduce Ms , and abnormal values indicate quality problems.

6. Test equipment

Magnetic saturation tester : such as Koerzimat MS, Sigmameter , equipped with a strong magnetic field generator (1.52 T) and a magnetic flux detection system (accuracy ±0.5%).
Precision balance : accuracy ±0.01 g, measure sample mass.
Calibration standard sample : pure cobalt (Ms = 16.1 μTm³ / kg) or cemented carbide with known Ms.
Constant temperature device : test environment temperature 2025°C.
Demagnetization equipment (optional): remove residual magnetization of samples.

7. Sample requirements

Type : Powder before sintering or sintered product (such as tools, molds).
Shape and size : Any shape (such as cylinder, cube), size 510 mm, mass 0.550 g.
Surface : Clean, free from oil, oxide layer or mechanical damage.
Uniformity : The internal composition is uniform, without cracks or pores.
Sampling : At least 3 representative samples per batch .

8. Testing steps

Equipment Calibration :
Calibrated using pure cobalt or certified carbide samples, Ms error <±1%.
Record calibration data (standard sample Ms , date).
Sample preparation :
Clean the sample to remove oil, dirt and oxides.

Weigh the mass (in g, ±0.01 g).

If there is residual magnetization, use demagnetization equipment.

Magnetic saturation measurement :

The sample was placed in a strong magnetic field (1.52 T) to ensure that the cobalt phase was fully magnetized.

Measure the magnetic flux and record Ms (μTm³ / kg).

The measurement was repeated 3 times and the average value was taken. The single deviation was <±0.5%.

Data Records :

Record the sample number, mass, Ms value, and test conditions (magnetic field strength, temperature).

If Ms is abnormal, check the sample or equipment and retest if necessary.

9. Calculation and Expression

Magnetic saturation intensity :

$$\mathrm{Ms} = \frac{\text{磁通量}}{\text{样品质量}}$$

The unit is μTm³ / kg, with 3 decimal places (eg 1.610 μTm³ / kg).

Cobalt Content :

$$\text{钴质量分数}(\%) = \frac{\mathrm{Ms}}{16.1} \times 100$$

Keep 1 decimal place (eg 10.0%).

Relative magnetic saturation (S) :

$$S = \frac{\mathrm{Ms}_{\text{测量}}}{\mathrm{Ms}_{\text{理论}}}$$

Ms theory is based on the cobalt content, S<0.9 indicates η phase, and S>1.1 indicates free carbon.

Accuracy : Repeatability error <±1%, batch-to-batch deviation <±2%.

10. Results Analysis

Normal range : The Ms of the sintered alloy is 85-95% of the theoretical value (because part of the cobalt dissolves into WC or forms a non-magnetic phase).

Abnormal situation :

Ms is low (<90%): insufficient η phase, oxide, and cobalt content.

Ms is too high (>110%): free carbon and cobalt content exceed the standard.

Supplementary verification : Abnormal Ms needs to be combined with metallographic analysis (microscope observation of η phase, free carbon), X-ray diffraction or chemical analysis (ICP measurement of cobalt content).

11. Test Report

Report includes:
Standard reference: ASTM B88624.
Sample information: number, type (powder/sintered), shape, mass, batch.
Test conditions: device model, magnetic field strength, temperature.
Results: Ms value, cobalt content, relative magnetic saturation.
Calibration information: Ms value of standard sample, calibration date.
Description of exception: Reason for deviation (e.g. η phase, free carbon).
Tester: Name, date, signature.
Laboratory information: name, address, certification qualifications.

12. Precision and Bias

Repeatability : With the same equipment and operator, the deviation of 3 measurements is <±0.5%.
Reproducibility : The batch-to-batch deviation is <±2% across different laboratories and equipment.
Deviation : No systematic deviation, Ms values traceable to SI units.
Influencing factors : uneven samples, uncalibrated equipment, and environmental magnetic field interference.

13. Notes

Equipment Calibration : Monthly or every 1000 tests, using pure cobalt or certified samples.
Sample homogeneity : avoid cracks, pores or uneven composition.
Environmental control : no strong magnetic field interference, temperature 2025°C.
Safety : Follow the equipment operating procedures and avoid the influence of strong magnetic fields.
Data verification : Repeat testing of abnormal results, combined with metallographic or chemical analysis.

14. Appendix

Appendix A : Relationship between magnetic saturation and carbon content.
Typical alloys: YG6 (6% cobalt, Ms≈0.97 μTm ³ /kg), YG8 (8% cobalt, Ms≈1.29 μTm ³ /kg).
η phase reduction Ms 1020%, free carbon reduced by 510%.
Appendix B : Equipment Calibration Guide.
Calibration frequency, standard sample requirements, error control.
Appendix C : Error sources and controls.
Sample preparation, equipment stability, environmental interference.

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Appendix:

GB/T 38492015 Determination of magnetic saturation value of cobalt in cemented carbide

Issue date : December 10, 2015

Implementation date : July 1, 2016

Status : Currently valid

Scope of application : This standard specifies the method for determining the magnetic saturation of cobalt in cemented carbide. It is applicable to cemented carbide containing ferromagnetic binder (mainly cobalt, mass fraction ≥ 3%), and is used for quality control, cobalt content verification and carbon balance assessment.

1. Scope

This standard describes a non-destructive method for determining **the magnetic saturation value** (Ms) of cobalt in cemented carbides for the purpose of assessing the cobalt content, carbon balance and alloy quality.

Applicable to:

Sintered carbide products (such as tools, molds, drills).

Cemented carbide powder before sintering (depending on equipment capabilities).

Purpose of the test:

Verify that the cobalt content meets specifications (e.g. YG6, YG8).

Indirect assessment of carbon content, detection of η phase (Co3W3C) or free carbon.

Evaluate the quality of the sintering process and identify non-magnetic impurities such as oxides.

Unit: SI units are used. The magnetic saturation value is expressed as μTm^3 / kg or $kA \cdot m^2$ / kg.

2. Normative References

GB/T 3848 : Chemical analysis method for cemented carbide (used to supplement the verification of cobalt content).
GB/T 4198 : Sampling and specimen preparation methods for cemented carbide.
ISO 3326:2013 : Method for determination of magnetic saturation of cobalt in cemented carbide (This standard is consistent with ISO 3326 in technical content and the translation is equivalent).
ASTM B886 : Method for determination of magnetic saturation of cemented carbide (reference standard, similar method).

3. Terms and Definitions

Cemented carbide : A composite material composed of a hard phase (such as tungsten carbide WC, titanium carbide TiC) and a ferromagnetic bonding phase (such as cobalt, nickel).
Cobalt Magnetic Saturation (Ms) : The value of the maximum magnetization intensity of the cobalt binder phase under a strong magnetic field, unit: μTm^3 / kg, reflecting the cobalt content and purity.
Ferromagnetic bonding phase : ferromagnetic metals such as cobalt (Co) and nickel (Ni), with cobalt as the main bonding agent.
η phase (Eta Phase) : Non-magnetic carbides (such as Co3W3C) formed when carbon is insufficient , reducing magnetism and toughness.
Free Carbon : Non-magnetic carbon that precipitates when there is excess carbon, weakening the strength.
Magnetic saturation constant : pure cobalt Ms is 16.116.3 μTm^3 /kg (ScienceDirect, 2020).

4. Principle

The magnetism of cemented carbide comes from the cobalt binder phase, and the hard phase (such as WC) does not contribute to magnetism.
Under strong magnetic fields (typically 1.52 T), the cobalt phase reaches magnetic saturation and Ms is proportional to the cobalt content. The Ms constant of pure cobalt is 16.1 μTm^3 / kg (typical value).
cobalt content: Ms ÷ 16.1 μTm^3 /kg ≈ Cobalt mass fraction. For example, Ms =1.61 μTm^3 / kg means the cobalt content is about 10%.
Influence of non-magnetic impurities:
η phase or oxides reduce Ms 1020%, indicating insufficient carbon.
Free carbon reduction Ms 510%, indicating excess carbon.
The test is non-destructive and independent of sample shape and size (within the limits of the equipment).

5. Apparatus

Magnetic analyzer : such as Koerzimat MS, Sigmameter , or domestic equipment (such as

magnetic saturation tester from a Chinese instrument factory), equipped with:
Strong magnetic field generator (1.52 T, to ensure saturation of the cobalt phase).
Magnetic flux detection system (accuracy ±0.5%).
Precision balance : accuracy ±0.01 g, measure sample mass.
Calibration standard : pure cobalt (Ms = 16.1 μTm³ / kg) or cemented carbide samples with known Ms , traceable to SI units.
Constant temperature device : The test environment temperature is controlled at 2025°C to avoid thermal effects.
Demagnetization equipment (optional): remove residual magnetization of samples.

6. Test Specimen

Type : Sintered carbide products (preferred), or powder before sintering (depending on equipment capabilities).
Shape and size : Any shape (such as cylinder, cube, tool blank), size 510 mm, mass 0.550 g.
Surface requirements : clean, free of oil, oxide layer or mechanical damage.
Homogeneity : The internal composition is uniform, without obvious cracks or pores.
Sampling : According to GB/T 4198, at least 3 representative samples per batch .

7. Test steps (Procedure)

Equipment Calibration :
The instrument is calibrated using pure cobalt or certified carbide samples, and the Ms error is controlled within ±1%.
Record the calibration data (standard sample Ms value, calibration date).
Sample preparation :
Clean the sample surface to remove oil, dirt and oxides.
Weigh the sample mass using a precision balance (m, unit: g, accuracy: ±0.01 g).
If the sample has residual magnetization, use demagnetization equipment.
Magnetic saturation measurement :
Place the sample in a strong magnetic field (1.52 T) of a magnetic analyzer to ensure that the cobalt phase is fully magnetized.
Measure the magnetic flux and record Ms (in μTm³ / kg).
The measurement was repeated 3 times and the average value was taken. The deviation of a single measurement was <±0.5%.
Data Records :
Record the sample number, mass, Ms value and test conditions (temperature, magnetic field strength).
If Ms is abnormal, check the sample or equipment and retest if necessary.

8. Calculation and Expression of Results

Magnetic saturation value :

$$Ms = \frac{\text{磁通量}}{\text{样品质量}}$$

The unit is μTm³ / kg, with 3 decimal places (eg 1.610 μTm³ / kg).

Cobalt Content :

$$\text{钴质量分数 (\%)} = \frac{Ms}{16.1} \times 100$$

Keep 1 decimal place (eg 10.0%).

Relative magnetic saturation (S) :

$$S = \frac{Ms_{\text{测量}}}{Ms_{\text{理论}}}$$

Ms theory is based on the cobalt content, S<0.9 indicates η phase, and S>1.1 indicates free carbon.

Precision : Result accuracy ±1%, batch-to-batch variation <±2%.

9. Results Analysis

Normal range : The Ms of the sintered alloy is usually 85-95% of the theoretical value (because part of the cobalt dissolves into WC or forms a non-magnetic phase).

Abnormal situation :

Ms is low (<90%): η phase, oxide or insufficient cobalt content may exist.

Ms is too high (>110%): There may be excessive free carbon or cobalt content.

Supplementary verification : Abnormal results need to be combined with metallographic analysis (microscope observation of η phase, free carbon), X-ray diffraction (XRD) or chemical analysis (measurement of cobalt content according to GB/T 3848).

10. Test Report

The report should include:

Standard reference: GB/T 38492015.

Sample information: number, type (powder/sintered), shape, mass, batch.

Test conditions: device model, magnetic field strength (T), ambient temperature (°C).

Results: Ms value (μTm³ / kg), cobalt content (%), relative magnetic saturation (S).

Calibration information: Ms value of standard sample, calibration date.

Description of exceptions: If there are deviations, describe possible causes (e.g. η phase, free carbon).

Tester: Name, date, signature.

Laboratory information: name, address, accreditation (if applicable).

11. Precision and Bias

Repeatability : With the same equipment and operator, the deviation of 3 measurements is <±0.5%.

Reproducibility : The batch-to-batch deviation is <±2% in different laboratories and equipment.

Bias : No systematic bias, Ms values are traceable to SI units, calibration ensures accuracy.

Influencing factors : uneven samples, uncalibrated equipment, and environmental magnetic field interference.

12. Precautions

Equipment Calibration : Monthly or every 1000 tests, using pure cobalt or certified samples.
Sample uniformity : Avoid cracks, pores or uneven composition that affect Ms accuracy.
Environmental control : The test environment has no strong magnetic field interference and the temperature is 2025°C.
Safety : Comply with equipment operating procedures to avoid the impact of strong magnetic fields on personnel or electronic equipment.
Data Verification : Abnormal Ms The value needs to be repeated and confirmed by metallographic or chemical analysis.

13. Annexes

Appendix A (informative) : Relationship between cobalt magnetic saturation and carbon content.
Typical alloy Ms range: YG6 (6% cobalt, Ms≈0.97 μTm ³ /kg), YG8 (8% cobalt, Ms≈1.29 μTm ³ /kg).
η phase reduction Ms 1020%, free carbon reduced by 510%.
Appendix B (informative) : Equipment calibration guide.
Calibration frequency (monthly or every 1000 tests), standard sample requirements.
Appendix C (information only) : Error source analysis.
Sample inhomogeneity, uncalibrated equipment, environmental magnetic field interference, etc.

14. Links to related standards

ISO 3326:2013 : Determination of magnetic saturation of cobalt in cemented carbide. GB/T 3849 is equivalent to it and has the same technical content.
ASTM B88624 : Method for determination of magnetic saturation of cemented carbide, similar approach, covers both powders and sintered products.
GB/T 3848 : Chemical analysis methods for cemented carbide, supplementary verification of cobalt content.
GB/T 3850 : Method for determination of coercivity of cemented carbide, combined with cobalt magnetic testing, can comprehensively evaluate the microstructure.

GB/T 3850 : Determination method of coercivity of cemented carbide

1 Scope

This standard specifies the method for determining the coercivity (Hc) of cemented carbide materials and products. This method is applicable to tungsten carbide-based cemented carbides (such as WC-Co alloys, typical grades include YG6, YG8, etc.) with cobalt (Co) as the binder phase. By measuring the coercivity, the grain size, cobalt content distribution and microstructural integrity of the cemented carbide are indirectly characterized. This method can be used for quality control in the production process, product acceptance and non-destructive testing in research and development.

This standard does not apply to non-cobalt-based cemented carbides (such as nickel-based or iron-based cemented carbides) or non-magnetic materials.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.
GB/T 3848 Determination of cobalt content in cemented carbide
GB/T 3849 Test method for magnetic properties of cemented carbide
GB/T 223.1 Chemical analysis methods for steel and alloys
GB/T 230.1 Rockwell hardness test for metallic materials Part 1: Test method
ISO 3326:2013 Method for determination of coercivity of cemented carbide
ASTM B887 Standard for Determination of Coercivity of Cemented Carbide

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 **Coercive Force (Hc)**

In cemented carbide, the reverse magnetic field strength required to reduce the magnetization intensity of the cobalt binder phase from the saturation state to zero, the unit is kA/m (kiloampere /meter).

3.2 **Magnetic Saturation (Ms)**

Under the action of an external magnetic field (usually >1.5 T), the cobalt phase reaches the state of maximum magnetization intensity, with the unit of μTm³ / kg (magnetic moment per kilogram of material).

3.3 **Hardmetal is a composite material made of tungsten carbide (WC)**

as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.4 **Grain Size The average size of**
tungsten carbide particles in cemented carbide , expressed in micrometers (μm), affects the coercive force value.

3.5 **η Phase (Eta Phase)**
is a brittle phase formed in cemented carbide due to insufficient carbon content. Its chemical formula is Co_3W_3C , which will reduce magnetic properties and toughness.

3.6 **Free Carbon:**
Carbon precipitated due to excessive carbon content in cemented carbide, affecting magnetic properties and hardness.

4 Principle

The coercivity of cemented carbide comes from the ferromagnetism of the cobalt binder phase (Curie temperature is about 1145°C, magnetization intensity is 1.7-1.75 μB /atom), while the hard phase (such as WC) is a non-magnetic material and does not contribute to magnetism. The basic principle of the coercivity test is as follows: First, the cobalt phase is fully magnetized to saturation under the action of an external strong magnetic field (1.5-2 T), and then a gradually increasing reverse magnetic field is applied to measure the magnetic field intensity that makes the magnetization intensity drop to zero, that is, the coercivity (Hc). The coercivity is inversely proportional to the cobalt phase grain size. The Hc of fine-grained cemented carbide (grains 0.2-0.5 μm) is usually 25-40 kA/m, and the Hc of coarse-grained cemented carbide (grains>5 μm) is 5-10 kA/m. In addition, the coercivity is also affected by the cobalt content, microstructural uniformity and defects (such as η phase or pores), which can be used to evaluate the microstructure and process quality of cemented carbide.

5. Instruments and Equipment

5.1 **Coercivity meter**
Permanent magnet or electromagnetic coercivity meter can provide 1.5-2 T strong magnetic field, with measurement accuracy of ±1 kA/m and repeatability of <2%.

5.2 **Magnetic analyzer**
such as Koerzimat 1.097 or Sigmameter 2.068 can measure coercivity and magnetic saturation intensity simultaneously with an accuracy of ±0.5%.

5.3 **The vibrating sample magnetometer (VSM)**
is used for high-precision measurements with an error of ±0.1 kA/m and is suitable for laboratory research.

5.4 **Balance**

with an accuracy of ±0.01 g, used to weigh the sample mass.

5.5 **Cleaning tools**
include ethanol and non-magnetic tweezers for cleaning the sample surface.

5.6 The test environment temperature is controlled **in a constant temperature box** at 20-25°C and the humidity is <60%.

5.7 **Metallographic microscope**
with magnification of 200x-500x is used to verify grain size and microstructure.

5.8 **X-ray diffractometer (XRD)**
is used to detect η phase (2θ≈40°) or free carbon (2θ≈26°).

6. Samples

6.1 **Sample requirements**
Shape: The specimen is cylindrical or cubic, with a size of 5-10 mm (diameter or side length).
Surface condition: The surface should be flat, free of cracks (length <5 μm), pores (porosity <0.05%) or oxide layer, and cleaned with ethanol if necessary.
Homogeneity: composition deviation <0.1 wt %, grain size fluctuation <5%, avoiding internal defects affecting the measurement.
Quantity: Each batch shall have no less than 3 samples , and the samples shall come from the same sintering process.

6.2 **Sample preparation**
Cut the specimens from carbide blanks or finished products (e.g. tools, dies) to avoid stress introduction during cutting (stress < 100 MPa).
If there is an oxide layer or oil on the surface of the sample, wipe it with ethanol and dry it.
Weigh the sample (accuracy ±0.01 g) and record the sample number.

7 Test methods

7.1 **Test conditions**
Ambient temperature: 20-25°C, temperature fluctuation <±2°C, to avoid affecting the magnetic properties of the cobalt phase .
Ambient humidity: <60%, to prevent moisture from causing micro-corrosion of the cobalt phase (magnetization intensity decreases by <2%).
Magnetic field interference: There is no strong magnetic field interference in the test area (<0.1 mT).

7.2 **Instrument Calibration**
using standard samples (e.g. pure cobalt, Hc =5 kA/m, Ms =16.2 μTm³ / kg) with an error of <±1%.

Calibration cycle: once a month, or before each test.
Check the magnetic field strength (1.5-2 T) to ensure that the cobalt phase is fully magnetizable.

7.3 **Test steps**

Place the sample in the test area of the coercivity meter and fix it with a non-magnetic clamp to ensure that the sample does not move.
Apply a strong magnetic field (1.5-2 T) to fully magnetize the cobalt phase to saturation and maintain it for 5-10 seconds.
Gradually apply a reverse magnetic field and record the magnetic field strength when the magnetization intensity drops to zero, that is, the coercive force (Hc), in kA/m.
Each sample was measured 3 times and the average value was taken with a deviation of <2%.
Record the sample number, mass, Hc value and test conditions (temperature, humidity, instrument model).

7.4 **Data Processing**

The average of the three measured values for each sample was calculated as the final Hc value.
If the Hc value of the same batch of samples fluctuates by >10% (e.g. YG8 changes from 15 kA/m to 25 kA/m), it indicates uneven sintering and further testing is required.
based on the empirical formula Hc ≈ k/d (k is a constant, d is the grain size). For example, Hc = 30 kA/m corresponds to a grain size of about 0.2-0.5 μm .

8 Results Expression

The coercive force value is in kA/m, with one decimal place (eg 15.2 kA/m).
The test report should include:
a) sample number;
b) coercivity value (Hc);
c) test conditions (temperature, humidity);
d) instrument model and calibration status;
e) if the Hc value deviates from the target value by >±5% (e.g. YG6 target 18 kA/m, measured <17.1 or >18.9 kA/m), the possible reasons should be explained (e.g. η phase or grain abnormalities).

9 Precision and Bias

9.1 **Precision**

Hc value of repeated measurement of the same sample by the same operator and the same equipment within a short period of time is less than 2%.
Reproducibility: The deviation of Hc values measured by different laboratories, different operators, and different equipment is <5%.

9.2 **Bias**

Instrument calibration error: ±1 kA/m.
Sample inhomogeneity: Inhomogeneity in composition or grain size causes Hc to fluctuate by 5-

10%.

Environmental interference: Strong magnetic fields (>0.1 mT) cause Hc deviations >2%.

10 Influencing factors

10.1 **Grain size**

The smaller the grain size, the higher the coercivity. Fine-grained cemented carbide (grain size 0.2 μm) Hc is 30-40 kA/m, and coarse-grained cemented carbide (grain size 5 μm) Hc is 5-10 kA/m.

10.2 **Cobalt content**

The increase in cobalt content (from 6% to 15%) makes the cobalt phase magnetization easier to flip, and Hc decreases slightly (10-15%).

10.3 The formation of **carbon equilibrium**

η phase (Co_3W_3C) causes Hc to decrease by 5-10% (for example, YG8 decreases from 15 kA/m to 13 kA/m), and the influence of free carbon (C) is <2%.

10.4 **Sintering Process**

High temperature (>1500°C) leads to coarsening of grains and a decrease in Hc from 20 kA/m to 8 kA/m.

Hot isostatic pressing (HIP, 150 MPa, 1350°C) improves microstructural homogeneity and Hc increases by 5-10%.

10.5 **Defective**

porosity > 0.1% or residual stress (> 100 MPa) causes Hc to fluctuate by 10-15%, and density needs to be optimized (> 99.5%).

10.6 **Environmental factors**

High temperature (800°C) reduces Hc by 5-8% (e.g. YG10 drops from 18 kA/m to 16 kA/m).

Damp heat (40°C, 90% humidity) affects <2%.

11 Application of test results

11.1 **Performance Classification**

Hc >25 kA/m: suitable for high hardness tools (such as PCB drill bits, HRA >92, life >4 hours).

Hc <10 kA/m: suitable for high toughness molds (such as mining drill bits, KIC >15 $MPa \cdot m^{1/2}$, life >200 hours).

11.2 **Process Optimization Abnormal**

Hc (fluctuation > 10%) indicates coarse grains or uneven sintering. The sintering temperature (1350-1450°C) can be adjusted or grain inhibitors (such as VC 0.2-0.5 wt %) can be added.

11.3 **Defect Detection A 5-10% decrease**

in Hc (e.g. YG8 from 15 kA/m to 13 kA/m) may be due to η phase, and the carbon content needs to be adjusted (target 6.0±0.2 wt %).

11.4 **Application Examples**

In the cutting of aviation steel (cutting speed 250 m/min), a tool containing 10% Co passed the Hc test (18 kA/m), ensuring hardness HRA 90 and impact resistance, and the tool life reached 3.5 hours.

12 Notes

12.1 Instrument Calibration

Before testing, calibrate the instrument to an error of <±1% to avoid systematic deviation.

12.2 Specimen Homogeneity

The specimens shall be free of cracks (<5 μm), pores (<0.05%), composition deviation <0.1 wt %, and grain size fluctuation <5%.

12.3 Environmental Control

The test area has no strong magnetic field (<0.1 mT), the temperature is 20-25°C, and the humidity is <60%.

12.4 Comprehensive Verification

If the Hc value is abnormal (deviation > 5%), observe the grain boundaries with a metallographic microscope (magnification 500x), or use ICP to measure the cobalt content (accuracy ± 0.05 wt %).

13 Test Report

The test report should include the following:

Standard number: GB/T 3850;

Sample description: brand, batch, size;

Test conditions: temperature, humidity, magnetic field interference;

Instrument information: model, calibration status;

Test results: coercivity value (Hc , kA/m), deviation analysis;

Abnormal description: If the Hc value deviation is >5%, explain the possible cause;

Test date: such as May 21, 2025;

Tester: Signature.

14 Appendix (Informative Appendix)

Appendix A Typical coercivity values

Table A.1 Coercivity values of common cemented carbide grades

Brand	Cobalt content (wt %)	Grain size (μm)	Coercive force (kA/m)
YG6	6	1-2	15-20
YG8	8	2-3	10-15
YG10	10	2-4	8-12
Nano alloy	8	0.05-0.2	50-60

Appendix B Error Analysis

B.1 **Instrument error**

±1 kA/m .

B.2 **Sample inhomogeneity Inhomogeneous**

composition or grain size causes Hc to fluctuate by 5-10%.

B.3 **Environmental interference**

Strong magnetic field (>0.1 mT) causes Hc deviation>2%.

Appendix C Improvement Suggestions

C.1 Use high-precision vibrating sample magnetometer (VSM) with an error of ±0.1 kA/m.

C.2 Use artificial intelligence (AI) to analyze Hc data and predict grain size and defects with an accuracy of >90%.

C.3 Introduce high-temperature coercivity test equipment (supporting 800-1000°C testing) to evaluate high-temperature performance.

C.4 Combine infrared spectroscopy to monitor sintering atmosphere, dynamically adjust sintering parameters, and reduce Hc fluctuations (<2%).

Appendix D Test Data Examples

Table D.1 YG8 cemented carbide coercivity test data

Sample No.	Mass (g)	Hc measurement value (kA/m)	Average Hc (kA/m)	deviation(%)
YG8-001	5.02	14.8, 15.0, 14.9	14.9	1.3
YG8-002	5.05	15.1, 15.3, 15.0	15.1	1.9
YG8-003	4.98	14.7, 14.9, 14.8	14.8	1.3

Appendix E Environmental Impact Data

Changes in Hc value under different environmental conditions

Environmental conditions	Hc (kA/m)	change(%)
Standard (25°C, 50% humidity)	15.0	-
High temperature (800°C)	13.8	-8.0
Damp heat (40°C, 90% humidity)	14.7	-2.0

GB/T 3848 Determination of cobalt content in cemented carbide

1 Scope

This standard specifies the method for determining the cobalt (Co) content in cemented carbide. This method is applicable to cemented carbide materials and products (such as grades YG6, YG8, etc.) with tungsten carbide (WC) as the hard phase and cobalt as the binder phase. The weight percentage (wt %) of cobalt is determined by chemical analysis or instrumental analysis. This method can be used for quality control in the production process, product acceptance and component analysis in research and development.

This standard does not apply to non-cobalt-based cemented carbides (such as nickel-based or iron-based cemented carbides) or materials containing other significant interfering elements.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.
GB/T 3849 Test method for magnetic properties of cemented carbide
GB/T 223.1 Chemical analysis methods for steel and alloys
GB/T 6682 Specifications and test methods for water used in analytical laboratories
ISO 3909:1976 Determination of cobalt content in cemented carbides - Potentiometric method
ASTM E1019 Standard Test Method - Analysis of Chemical Composition of Alloys

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Cobalt Content:

The weight percentage (wt %) of cobalt in cemented carbide, based on the total mass, reflects the proportion of the binder phase.

3.2 Hardmetal is a composite material made of tungsten carbide (WC)

as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.3 η Phase (Eta Phase)

is a brittle phase formed in cemented carbide due to insufficient carbon content. Its chemical formula is Co_3W_3C , which may interfere with the determination of cobalt content.

3.4 Free Carbon The

carbon precipitated from cemented carbide due to excessive carbon content may affect the analysis

results.

3.5 Potentiometric Titration is

a titration method that uses electrodes to measure the change in solution potential to determine the endpoint.

4 Principle

The principle of determining the cobalt content in cemented carbide is based on chemical decomposition and quantitative analysis. The sample is decomposed by acid or melt to convert cobalt into a soluble compound (such as cobalt chloride), and then its content is determined by gravimetric method, potentiometric titration or spectroscopic analysis. The potentiometric titration method uses the stable complex formed by cobalt and EDTA (ethylenediaminetetraacetic acid) to determine the end point by the potential change; the spectroscopic analysis method (such as atomic absorption spectroscopy or inductively coupled plasma emission spectroscopy) is based on the characteristic absorption or emission spectrum of cobalt for quantification. η phase or free carbon may interfere with the determination and need to be removed by pretreatment.

5. Instruments and Equipment

5.1 Analytical balance

with an accuracy of ±0.0001 g, used for weighing samples and reagents.

5.2 Potentiometric titrator

equipped with glass electrode and reference electrode, with accuracy of ±0.1 mV, suitable for potentiometric titration.

5.3 Atomic absorption spectrometer (AAS)

with a wavelength of 240.7 nm and a detection limit of 0.01 μg /mL was used for the determination of cobalt content.

5.4 The detection limit of inductively coupled plasma optical emission spectrometer (ICP-OES)

is 0.001 μg /mL, which is suitable for multi-element analysis.

5.5 The temperature control range of the constant temperature water bath is 20-100°C, with an accuracy of ±1°C.

5.6 A heating plate or electric furnace

with a temperature range of 100-600°C is used for sample decomposition.

5.7 Acid distillation units

are used to remove interfering elements (such as arsenic and antimony).

5.8 The capacities of pipettes and volumetric flasks
are 5 mL, 10 mL, 25 mL, and 100 mL, with an accuracy of ±0.1 mL.

6 Reagents

6.1 Nitric acid (HNO_3) of
high purity, concentration 65%-68%.

6.2 Hydrochloric acid (HCl)
of high purity, concentration 36%-38%.

6.3 Sulfuric acid (H_2SO_4) is
of high purity, with a concentration of 95%-98 **% .**

6.4 EDTA standard solution
concentration is 0.01 mol/L, use after calibration.

6.5 Buffer solution
pH 5.0-6.0, containing ammonium acetate and ammonia.

6.6 Indicators
such as Xylenol Orange are used to determine the endpoint of titration.

6.7 Deionized water
complies with GB/T 6682 Grade 1 water standard.

7 Specimens

7.1 Sample requirements
Shape: The sample is powder, granules or small pieces with a mass of 0.2-0.5 g.
Homogeneity: composition deviation <0.1 wt %, grain size fluctuation <5%.
Surface condition: No oil or oxide layer, clean with ethanol if necessary.

7.2 Sample preparation
Take a representative sample from the cemented carbide blank or finished product and crush it to a particle size of <0.1 mm.
After being kept in a desiccator at a constant temperature (105°C, 1 h), the sample was cooled to room temperature and weighed (±0.0001 g).
Take 3-5 parallel samples from each batch to ensure representative results.

8 Test methods

8.1 Potentiometric titration

8.1.1 Sample decomposition

Weigh 0.2 g of sample and place it in a 250 mL beaker.

Add 10 mL nitric acid and 5 mL sulfuric acid, heat until nearly dry, and cool.

Add 20 mL of hydrochloric acid, heat to dissolve the residue, and then cool and dilute to 100 mL.

8.1.2 Titration steps

Take 10 mL of the solution, add buffer solution (pH 5.5) and luteolin indicator .

Titrate with 0.01 mol/L EDTA standard solution and record the potential change to the endpoint.

Calculation formula:

$$钴含量\ (\mathrm{wt\%}) = \frac{C \times V \times M \times 58.93 \times 100}{m \times 1000}$$

8.1.3 Blank test

Carry out a blank test according to the same steps and deduct the blank value.

8.2 Atomic Absorption Spectroscopy (AAS)

8.2.1 Sample decomposition

Weigh 0.1 g of sample, add 5 mL of nitric acid and 2 mL of hydrochloric acid, and heat to dissolve.

After cooling , the volume was adjusted to 50 mL and filtered through a 0.45 μm filter membrane.

8.2.2 Measurement steps

Adjust the instrument wavelength to 240.7 nm and start the operation.

Cobalt concentration was determined using a standard series method in the range of 0.1-10 μg /mL.

Calculation formula:

$$钴含量\ (\mathrm{wt\%}) = \frac{C \times V \times 100}{m \times 1000}$$

8.2.3 Interference Elimination

If there is interference from iron or nickel, add an anti-interference agent (such as lanthanum salt).

8.3 Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

8.3.1 Sample decomposition

Weigh 0.1 g of sample, add 5 mL of nitric acid and 1 mL of hydrogen peroxide, and digest by microwave.

After cooling, dilute to 50 mL and filter for later use.

8.3.2 Measurement steps

Set the wavelength to 228.616 nm and calibrate the instrument.

cobalt concentration was determined by the standard curve method with a detection limit of 0.001

μg /mL.
The calculation formula is the same as 8.2.2.

8.3.3 Interference Elimination

If there is tungsten interference, adjust the background correction parameters.

9 Results Expression

cobalt content is expressed in wt % with 2 decimal places (eg 6.25%).
The test report should include:
a) Standard number: GB/T 3848;
b) Sample description: brand, batch, quality;
c) Test method: potentiometric titration, AAS or ICP-OES;
d) Result: cobalt content and deviation;
e) Test conditions: temperature, humidity;
f) Instrument model and calibration status;
g) Test date: such as May 21, 2025;
h) Tester: signature.

10 Precision and Bias

10.1 Precision

Repeatability: The deviation of cobalt content measured by the same operator, the same equipment and within a short period of time is <0.2%.
Reproducibility: The deviation of cobalt content measured by different laboratories and different operators is <0.5%.

10.2 Bias

Instrument error: AAS ±0.01 μg /mL, ICP-OES ±0.001 μg /mL.
Sample inhomogeneity: Composition deviation >0.1 wt % leads to result fluctuation of 0.3-0.5%.
Interfering elements: The bias can reach 1-2% when η phase or free carbon is not removed .

11 Influencing factors

11.1 Incomplete decomposition of the sample (e.g., tungsten residue) may result in an underestimation of the cobalt content by 0.5-1%.

11.2 Interfering elements

Iron (>5%) and Nickel (>2%) may interfere with AAS determination and require pre-separation.

11.3 Acid Concentration

Too High Acidity (pH < 2) causes the EDTA titration endpoint to shift by 0.1-0.3%.

11.4 Environmental Conditions

High temperature (>40°C) or humidity (>70%) causes the solution to evaporate, with a deviation of <0.2%.

12 Application of test results

12.1 Quality Control

Verify that the cobalt content meets the design requirements, such as the YG6 target of 6 ± 0.2%.

12.2 Process Optimization

A low cobalt content indicates insufficient ingredients, while a high cobalt content indicates an excess of binder phase.

12.3 Prediction of properties

A cobalt content of 6-10% corresponds to high hardness (HRA 90-92), 10-15% corresponds to high toughness (KIC 12-15 MPa·m $^{1/2}$).

12.4 Example

In the production of cutting tools, YG8 with a cobalt content of 8.1% ensures a hardness of HRA 91 and a life of >3 hours.

13 Notes

13.1 The instrument shall be calibrated

using a standard cobalt sample with an error of <±0.1%.

13.2 Specimen Homogeneity

Ensure that the specimens are free of cracks, pores and have uniform composition.

13.3 The test room temperature is controlled to be 20-25°C and the humidity is <60%.

13.4 Safety Protection

Wear protective glasses during operation to avoid acid splashes.

14 Appendix (Informative Appendix)

Appendix A Typical Cobalt Content Values

Table A.1 Cobalt content of common cemented carbide grades

Brand	Cobalt content (wt %)	Hardness (HRA)	Toughness (KIC, MPa·m $^{1/2}$)
YG6	6.0±0.2	90-91	10-12

Brand	Cobalt content (wt %)	Hardness (HRA)	Toughness (KIC, MPa·m ¹ / ²)
YG8	8.0±0.2	89-90	12-14
YG10	10.0±0.3	88-89	14-16

Appendix B Error Analysis

B.1 Instrument error:
AAS ±0.01 μg /mL, ICP-OES ±0.001 μg /mL.

B.2 Operational error
The deviation of titration endpoint judgment is 0.1-0.2%.

B.3 Environmental influence
Humidity>70% causes a 0.2% deviation in the result.

Appendix C Improvement Suggestions
C.1 Use microwave digestion to improve decomposition efficiency and reduce tungsten residue.
C.2 Use ICP-MS to improve detection sensitivity, with a detection limit of <0.0001 μg /mL.
C.3 Introduce an automated titration system to reduce human errors.

Appendix D Test Data Examples
Table D.1 Test data of cobalt content in YG8 cemented carbide

Sample No.	Mass(g)	Cobalt content (wt %)	Average value (wt %)	deviation(%)
YG8-001	0.201	8.05, 8.10	8.08	0.37
YG8-002	0.203	8.00, 8.03	8.02	0.25
YG8-003	0.202	8.12, 8.09	8.11	0.37

Appendix E Impact of Interference Elements
Table E.1 Effects of different interfering elements on the determination of cobalt content

干扰元素	含量 (wt%)	偏差 (wt%)	消除方法
铁	5	0.6	加入掩蔽
镍	2	0.3	预分离
钨	10	1.0	微波消解

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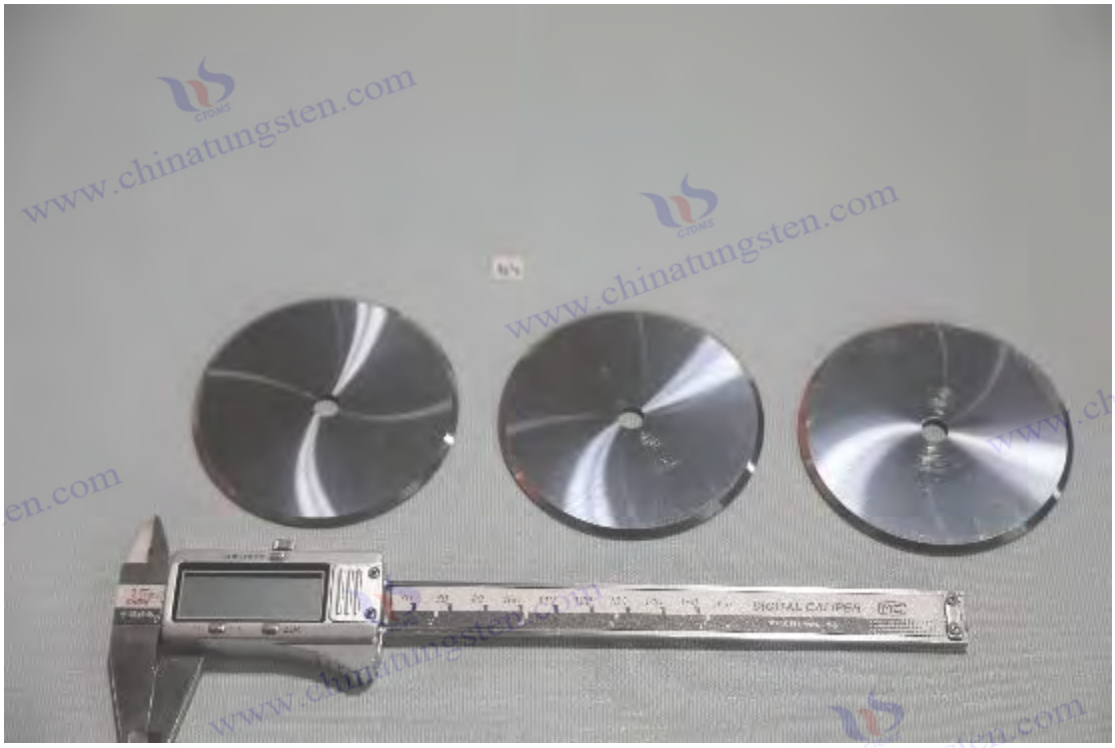

ISO 3909:1976

Determination of cobalt content in cemented carbide - potentiometric method

1 Scope

This international standard specifies a method for determining the cobalt (Co) content in cemented carbide by potentiometric method. This method is applicable to carbide and bonding metal powder mixtures without lubricant, pre-sintered or sintered cemented carbide of all grades, with a cobalt content greater than 1% (mass fraction, m/m). This method can be used for quality control in cemented carbide production, product acceptance and composition analysis in research and development.

This standard does not apply to cemented carbides with a cobalt content of less than 1%, or materials containing significant interfering elements (such as high content of iron and nickel).

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

ISO 5725 Precision (accuracy and precision) test methods and evaluation of results

ISO 11873 Cemented carbide - Terminology

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 **Cobalt Content:**
The weight percentage of cobalt in cemented carbide (m/m), based on the total mass, reflects the proportion of the bonding phase.

3.2 **Hardmetal is a composite material made of tungsten carbide (WC)**
as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.3 **η Phase (Eta Phase)**
is a brittle phase formed in cemented carbide due to insufficient carbon content. Its chemical formula is Co_3W_3C , which may interfere with the determination of cobalt content.

3.4 **Free Carbon:**
Carbon precipitated from cemented carbide due to excessive carbon content may affect the analysis results.

3.5 **Potentiometric Titration is**
a method of determining the titration endpoint by measuring the change in solution potential.

4 Principle
This method dissolves the cobalt in the cemented carbide sample into a soluble compound (such as cobalt chloride) by acid decomposition, and then determines the cobalt content by potentiometric titration. After the sample is decomposed by acid, the cobalt ions (Co^{2+}) in the solution form a stable complex with ethylenediaminetetraacetic acid (EDTA), and the endpoint is determined by potentiometric titration. Potentiometric titration uses electrodes (usually glass electrodes and reference electrodes) to monitor the sudden jump in the potential of the solution to determine the endpoint. η phase or free carbon may interfere with the determination and need to be removed by pretreatment (such as acid distillation or filtration).

5 Interference elements

5.1 **Iron (Fe)**
When the iron content is >5% (m/m), it may form a complex with EDTA, interfering with the titration of cobalt and needs to be removed by pre-separation (such as ion exchange).

5.2 **Nickel (Ni)**
When the nickel content is >2% (m/m), it may affect the endpoint of the potentiometric titration and needs to be eliminated by pre-separation or addition of a masking agent (such as ammonia water).

5.3 **Tungsten (W)**
Tungsten may form precipitates (such as tungstic acid) that interfere with solution clarification and must be removed by thorough dissolution and filtration.

5.4 **η phase and free carbon**

η phase may lead to an underestimate of the cobalt content, and free carbon may adsorb cobalt ions and need to be treated by pre-sintering or acid distillation.

6 Reagents

6.1 **Nitric acid (HNO_3) analytical**
grade, concentration 65%-68%.

6.2 **Hydrochloric acid (HCl)**
of analytical grade, concentration 36%-38%.

6.3 **Sulfuric acid (H_2SO_4) of**
analytical grade , concentration 95%-98%.

6.4 The concentration **of EDTA standard solution**
is 0.01 mol/L and it should be calibrated with zinc standard solution before use.

6.5 **Buffer solution**
pH 5.0-6.0 , containing ammonium acetate and ammonia.

6.6 **Indicator (auxiliary)**
Xylenol Orange, used to observe the titration endpoint (optional).

6.7 Resistivity **of deionized water ≥ 18** MΩ·cm .

7 Instruments and Equipment

7.1 **Analytical balance**
with an accuracy of ±0.0001 g is used to weigh samples and reagents.

7.2 **The potentiometric titrator**
is equipped with a glass electrode and a reference electrode (such as an Ag/AgCl electrode) with an accuracy of ±0.1 mV.

7.3 **A heating plate or electric furnace**
with a temperature range of 100-600°C is used for sample decomposition.

7.4 The temperature control range of **the constant temperature water bath**
is 20-100°C, with an accuracy of ±1°C.

7.5 **Acid distillation apparatus**

is used to remove interfering elements (such as arsenic and antimony).

7.6 The capacities of **pipettes and volumetric flasks**
are 5 mL, 10 mL, 25 mL, and 100 mL, with an accuracy of ±0.1 mL.

7.7 **Filter device**
with 0.45 μm filter membrane for solution filtration.

8. Samples

8.1 **Sample requirements**
Shape: The sample is powder, granules or small pieces with a mass of 0.2-0.5 g.
Homogeneity: composition deviation <0.1% (m/m), grain size fluctuation <5%.
Surface condition: No oil or oxide layer, clean with ethanol if necessary.

8.2 **Sample preparation**
Take a representative sample from the cemented carbide blank or finished product and crush it to a particle size of <0.1 mm.
Dry at 105°C for 1 h, cool to room temperature and weigh (±0.0001 g).
Take 3-5 parallel samples from each batch to ensure representative results.

9 Test steps

9.1 Sample decomposition
Weigh 0.2 g of sample (±0.0001 g) and place it in a 250 mL beaker.
Add 10 mL nitric acid and 5 mL sulfuric acid, heat on a hot plate (200-250°C) until nearly dry, and cool.
Add 20 mL of hydrochloric acid and continue heating (150°C) until the residue is completely dissolved, then cool.
Dilute with deionized water to 100 mL, filter (0.45 μm filter membrane) and set aside.

9.2 Potentiometric titration
Take 10 mL of the test solution, place it in a 100 mL titration cup, and add buffer solution (pH 5.5).
Add 2-3 drops of luteolin indicator (optional) and observe the color change.
Monitor the potential with a potentiometric titrator, add 0.01 mol/L EDTA standard solution, and record the potential jump point (end point).
Each sample was measured 3 times and the average value was calculated.

9.3 Blank test
Carry out a blank test following the same procedure and deduct the blank value (usually <0.05% cobalt content).

9.4 Calculation

cobalt content is calculated as follows:

$$钴含量\ (\%) = \frac{C \times V \times M \times 100}{m \times 1000}$$

in:

- C：EDTA 标准溶液浓度 (mol/L)；
- V：消耗 EDTA 体积 (mL)；
- M：钴摩尔质量 (58.93 g/mol)；
- m：试样质量 (g)。

10. Result Expression

cobalt content is expressed as mass fraction (%), with 2 decimal places (such as 6.25%).

The test report should include:

a) Standard number: ISO 3909:1976;

b) Sample description: brand, batch, quality;

c) Test conditions: temperature, humidity;

d) Instrument model and calibration status;

e) Results: cobalt content and deviation;

f) Test date: such as May 21, 2025;

g) Tester: signature.

11 Precision and Bias

11.1 **Precision**

Repeatability: The deviation of cobalt content measured by the same operator, the same equipment and within a short period of time is <0.2%.

Reproducibility: The deviation of cobalt content measured by different laboratories and different operators is <0.5%.

11.2 **Bias**

Instrument error: potentiometric titrator ±0.1 mV.

Sample inhomogeneity: Composition deviation > 0.1% (m/m) leads to result fluctuation of 0.3-0.5%.

Interfering elements: The bias can reach 1-2% when η phase or free carbon is not removed .

12 Influencing factors

12.1 Incomplete decomposition **of the sample (e.g., tungsten residue) may result in an underestimation of**
the cobalt content by 0.5-1%.

12.2 **Interfering elements such as** iron (>5%) and nickel (>2%) may interfere with titration and

require pre-separation.

12.3 **Acid concentration**

Too high acidity (pH < 2) causes the EDTA titration endpoint to shift by 0.1-0.3%.

12.4 **Environmental Conditions**

High temperature (>40°C) or humidity (>70%) causes the solution to evaporate, with a deviation of <0.2%.

13 Application of test results

13.1 **Quality control**

verifies whether the cobalt content meets the design requirements, such as YG6 target 6±0.2%.

13.2 **Process Optimization**

A low cobalt content indicates insufficient ingredients, while a high cobalt content indicates an excess of binder phase.

13.3 **Prediction of properties**

A cobalt content of 6-10% corresponds to high hardness (HRA 90-92), 10-15% corresponds to high toughness (KIC 12-15 MPa·m $^{1/2}$).

13.4 **Example**

In the production of mining drill bits, YG8 with a cobalt content of 8.05% ensures a hardness of HRA 90 and a life of >200 hours.

14 Notes

14.1 The instrument shall be calibrated

using standard cobalt solution with an error of <±0.1%.

14.2 Specimen Homogeneity

Ensure that the specimens are free of cracks, pores, and have uniform composition.

14.3 The test room temperature is controlled to be 20-25°C and the humidity is <60%.

14.4 Safety Protection

Wear protective glasses during operation to avoid acid splashes.

15 Appendix (Informative Appendix)

Appendix A Typical Cobalt Content Values

Table A.1 Cobalt content of common cemented carbide grades

Brand	Cobalt content (% m/m)	Hardness (HRA)	Toughness (KIC, MPa·m ¹ / ²)
YG6	6.0±0.2	90-91	10-12
YG8	8.0±0.2	89-90	12-14
YG10	10.0±0.3	88-89	14-16

Appendix B Error Analysis

B.1 **Instrument error**

Potentiometric titrator ±0.1 mV.

B.2 **Operational error**

The deviation of titration endpoint judgment is 0.1-0.2%.

B.3 **Environmental impact**

Humidity > 70% causes a 0.2% deviation in the results.

Appendix C Improvement Suggestions

C.1 Use microwave digestion to improve decomposition efficiency and reduce tungsten residue.

C.2 Introduce an automated titration system to reduce human error.

C.3 Use ICP-MS instead of potentiometric method, with a detection limit of <0.0001 μg /mL.

Appendix D Test Data Examples

Table D.1 Test data of cobalt content in YG8 cemented carbide

Sample No.	Mass(g)	Cobalt content (% m/m)	Average value (% m/m)	deviation(%)
YG8-001	0.201	8.05, 8.10	8.08	0.37
YG8-002	0.203	8.00, 8.03	8.02	0.25
YG8-003	0.202	8.12, 8.09	8.11	0.37

Appendix E Impact of Interference Elements

Table E.1 Effects of different interfering elements on the determination of cobalt content

Interference elements	Content (% m/m)	Deviation (% m/m)	Elimination method
iron	5	0.5	Add lanthanum salt
nickel	2	0.3	Pre-separation
Tungsten	10	1.0	Microwave digestion

Appendix:

Methods of expressing the hardness of cemented carbide and its conversion relationship

Hardmetal or Cemented Carbide is widely used in industrial fields such as cutting tools and molds due to its high hardness and wear resistance. Its hardness is a key performance indicator. The hardness expression method of cemented carbide mainly includes a variety of test standards and units, commonly used are Vickers hardness (HV), Rockwell hardness (HRA, HRC), Knoop hardness (HK), etc. The specific choice depends on the test conditions and industry practices. This article introduces the hardness expression method, test principle, applicable scenarios and conversion relationship of cemented carbide in detail, combining data and standards (such as ISO, ASTM, GB/T) to ensure accuracy and comprehensiveness.

Method for expressing the hardness of cemented carbide

The hardness test of cemented carbide is usually carried out by the following methods, due to its high hardness and composite material characteristics (such as tungsten carbide WC and cobalt Co binder phase):

1. Vickers Hardness (HV)

Definition : A specific load (such as 10 kgf , 30 kgf) is applied to the material surface through a diamond quadrangular pyramid indenter (diagonal angle 136°) to measure the diagonal length of the indentation and calculate the hardness value.

formula :

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

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

Unit : HV (e.g. HV10 means 10 kgf load).

Applicable scenarios :

Standard test for cemented carbide, widely used in ISO 3878, GB/T 7997 (Vickers hardness test of cemented carbide).

Suitable for high hardness materials (hardness range of carbide 14002200 HV) and high precision.

Different grain sizes (such as ultrafine grains <0.5 μm , medium grains 12 μm) are applicable.

Typical values :

YG6 (6% Cobalt): ~15001600 HV30.

YG8 (8% Cobalt): ~14001500 HV30.

Ultrafine -grained cemented carbide: ~18002200 HV30 (ScienceDirect, 2020).

Advantage :

Applicable to a wide hardness range (503000 HV).

Small indentation, suitable for thin and small samples, high precision.

Disadvantages : long test time (microscope is required for indentation measurement) and high requirements for surface finish.

2. Rockwell Hardness (HRA)

Definition : Use a diamond cone indenter (vertex angle 120°, tip radius 0.2 mm), apply a total load of 60 kgf (preload 10 kgf , main load 50 kgf), measure the indentation depth difference and calculate the hardness.

Formula :

$$HRA = 100 - \frac{h}{0.002}$$

Where h is the penetration depth (mm).

Unit : HRA.

Applicable scenarios :

Rapid testing of carbide tools and dies in accordance with ISO 3738 and GB/T 230.1.

Suitable for cemented carbide with higher hardness (HRA 8092), commonly used in industrial sites.

Typical values :

YG6: ~8990 HRA.

YG8: ~8889 HRA.

Ultrafine -grained cemented carbide: ~9092 HRA (Sandvik, 2023).

Advantage :

The test is fast and the reading is direct, suitable for batch testing.

It has low requirements on the surface and is easy to operate.

Shortcoming :

Less accurate than Vickers hardness and only suitable for higher hardness ranges (HRA > 70).

Not suitable for ultra-thin or tiny samples.

3. Rockwell hardness (HRC, secondary use)

Definition : Use a diamond cone indenter (same as HRA) with a total load of 150 kgf to measure the penetration depth.

Applicable scenarios :

Used for softer grades of cemented carbide (e.g. high cobalt content > 15%) or when compared with high speed steel.

It is less used in cemented carbide because the HRC range (2070) does not fully cover the high hardness of cemented carbide (ScienceDirect, 2020).

Typical values :
YG15 (15% Cobalt): ~6567 HRC.
Advantages : Commonly used when compared with tool steel and die steel hardness.
Disadvantages : high load, large indentation, not suitable for mainstream testing of cemented carbide.

4. Knoop Hardness (HK)

Definition : Use a diamond rhombus indenter (major-short axis ratio 7:1, angles 172.5° and 130°), apply a light load (such as 0.51 kgf), and measure the long diagonal length of the indentation.
formula :

$$\mathrm{HK} = \frac{14.229 \cdot F}{d^2}$$

Where F is the load (kgf) and d is the diagonal length of the indentation (mm).
Unit : HK.

Applicable scenarios :
Testing of thin layers, coatings or ultra-fine grain structures of cemented carbide in accordance with ASTM E384.
Suitable for small area or surface hardness analysis (such as carbide coating).

Typical values :
YG6:~16001700 HK0.5.
Ultrafine grain cemented carbide: ~20002300 HK0.5.

advantage :
Shallow indentation, suitable for thin samples or coatings.
High resolution, suitable for micro hardness testing.

shortcoming :
The test is complex and requires a high-precision microscope.
Low load, susceptible to surface defects.

5. Other representation methods (less commonly used)

Brinell hardness (HB) : Use a carbide ball indenter with a load of 3000 kgf , suitable for low hardness carbide (rare, because the indentation is too large).

Shore Hardness (HS) : Impact hardness test, rarely used for cemented carbide due to its low accuracy.

Mohs hardness : Cemented carbide is about 8.59 (close to corundum), which is only used for scientific comparison and is not accurate.

Data support :
Carbide hardness range: 14002200 HV, 8092 HRA (ISO 3878, GB/T 7997).
Typical grades: YG8 (14001500 HV, 8889 HRA), ultrafine grain (18002200 HV, 9092 HRA) (Sandvik, 2023).

Hardness unit conversion relationship
The hardness test of cemented carbide uses different units (HV, HRA, HRC, HK), which need to be converted according to the standard conversion table or empirical formula. The following are the conversion relationships and precautions:

1. Common conversion tables

The following is an approximate conversion of common hardness values of cemented carbide, based on ASTM E140 (hardness conversion table), GB/T 1172 (hardness conversion specification) and industry data:

HV	HRA	HRC	HK	Remark
1200	85.0	~60	~1250	Low cobalt cemented carbide (such as YG15)
1400	87.0	~63	~1450	General cemented carbide (such as YG8)
1500	88.0	~65	~1550	General cemented carbide (such as YG6)
1600	89.0	~66	~1650	Medium fine grain cemented carbide
1800	90.5	~68	~1850	Ultrafine Grain Cemented Carbide
2000	91.5	~70	~2050	High hardness cemented carbide
2200	92.0	~72	~2250	Extreme Hardness Carbide

Data source :
ASTM E14012b(2023): Hardness conversion table.
GB/T 11721999: Chinese hardness conversion standard.
Industry practice: Sandvik, Kennametal carbide hardness data (Sandvik, 2023).

2. Conversion formula (empirical formula)

Accurate conversion requires consideration of material properties. There is no unified formula for cemented carbide due to its composite structure (WC+Co). The following is a commonly used empirical formula for reference:
HV and HRA :

$$HRA \approx 100 - \frac{4000}{HV}$$

Example: HV=1500, HRA ≈ 100 4000/1500 ≈ 87.3.

HV and HRC (high hardness range of cemented carbide):

$$HRC \approx 0.035 \cdot HV + 12$$

Example: HV=1500, HRC ≈ 0.035 × 1500 + 12 ≈ 64.5.

HV and HK :

$$HK \approx HV \cdot (1.05 \text{至} 1.10)$$

Example: HV=1500, HK ≈ 1500 × 1.07 ≈ 1605.

Notice :

The conversion formula is approximate, with an error of ±25% due to different cemented carbide grain sizes and cobalt content.

In the high hardness range (HV > 1500), the HRC conversion error is large, so it is recommended to measure HRA or HV directly.

3. Conversion considerations

Material Difference

The hardness of cemented carbide is affected by the cobalt content (5-15%) and grain size (0.52 μm). The conversion needs to refer to the specific grade (such as YG6, YG8).

Test conditions :

HV: The load (1030 kgf) affects the result and needs to be indicated (e.g. HV30).

HRA: Suitable for cemented carbide, HRC is limited to low hardness grades.

HK: Low load (0.5 kgf), suitable for micro testing.

Standard reference : Use ASTM E140 or GB/T 1172 conversion table to avoid empirical formula errors.

Actual measurement is preferred : conversion is for reference only , direct testing of the target hardness unit is more accurate.

Data support :

YG8: HV30 ≈ 1400, HRA ≈ 88, HRC ≈ 63 (GB/T 7997).

Ultrafine -grained cemented carbide: HV30 ≈ 2000, HRA ≈ 91.5 (Sandvik, 2023).

Application of Cemented Carbide Hardness Testing

Quality control : Hardness testing verifies the performance of cemented carbide grades, such as YG6 (1500 HV, 89 HRA) for rough machining and ultra-fine grain (2000 HV, 91 HRA) for finishing.

Process optimization : Hardness reflects the sintering effect. Large grains (>2 μm) reduce hardness, and η phase (Co3W3C) reduces toughness (ISO 3326:2013).

Tool selection :

High hardness (HV 18002200): suitable for high-speed cutting of hard materials (stainless steel, titanium alloy).

Medium hardness (HV 14001600): suitable for general processing (cast iron, steel).

Compared with superhard materials :

Cemented carbide: 1400-2200 HV, lower than diamond (8000-10000 HV) and CBN (4500 HV). Cemented carbide has better toughness than superhard materials and is suitable for impact loads (Wikipedia, 2024).

In conclusion

The hardness of cemented carbide mainly includes:

Vickers hardness (HV) : 14002200 HV, high accuracy, suitable for standard testing (ISO 3878).

Rockwell hardness (HRA) : 8092 HRA, fast, commonly used in industry (GB/T 230.1).

Rockwell hardness (HRC) : 6570 HRC, limited to low hardness grades.

Knoop hardness (HK) : 15002300 HK, suitable for thin layer and micro testing (ASTM E384).

Conversion relationship :

HV and HRA: HRA ≈ 100 4000/HV.

HV and HRC: HRC ≈ 0.035 × HV + 12 (high hardness leads to large error).

HV and HK: HK ≈ HV × 1.051.10.

It is recommended to use the ASTM E140 and GB/T 1172 conversion tables, and direct testing of the target unit is preferred.

Carbide hardness testing is the key to quality control and tool selection. The appropriate method should be selected according to the grade (YG6, YG8), grain size and processing requirements. Conversion should be cautious and combined with actual measurement to ensure accuracy.

Appendix:

Characteristics, influencing factors, test methods, application cases and optimization measures of various properties of cemented carbide

Performance	Features	Influencing factors	Test Method	Application Cases	Optimization measures
Hardness	High hardness (14002200 HV, 8092 HRA), strong wear resistance, second only to superhard materials (such as diamond 8000 HV). Typical values: YG6 (1500 HV30, 89 HRA), YG8 (1400 HV30, 88 HRA), ultrafine grain (2000 HV30, 91 HRA) (Sandvik, 2023). Trend: Hardness increases exponentially with decreasing grain size .	Grain size: Ultrafine grain (<0.5 μm) hardness 18002200 HV, medium grain (12 μm) 14001600 HV. Cobalt content: 6% cobalt has high hardness, 15% cobalt hardness decreases by 1015%. Impurities: η phase reduces hardness by 510%, free carbon reduces by 35%. Sintering temperature: >1450°C, coarse grains, hardness decreases by 10%.	Vickers hardness (HV30, ISO 3878): 30 kgf load, diamond square pyramid indenter, indentation diagonal measurement. Rockwell hardness (HRA, GB/T 230.1): 60 kgf load, diamond cone indenter, indentation depth measurement. Error: ±2% (ASTM E18).	YG6 tool (1500 HV) processes cast iron at a speed of 150 m/min and has a life of 2 hours. Ultrafine grain tool (2000 HV) processes stainless steel at a speed of 300 m/min and has a life of 3 hours.	Using ultrafine powder (<0.5 μm), the hardness is increased to 2000 HV and the wear resistance is improved by 20%. Controlling the cobalt content to 68%, the hardness is increased by 510%. Sintering temperature is 13501400°C, reducing η phase (GB/T 3849). Adding TaC (0.51%) inhibits grain growth and increases the hardness by 5%.
Toughness	Medium toughness, impact resistance is better than superhard materials, lower than high-speed steel, suitable for medium and high-speed cutting. Typical values: YG6 (KIC 8 MPa·m $^{1/2}$), YG8 (10 MPa·m $^{1/2}$), YG15 (12 MPa·m $^{1/2}$) (ScienceDirect, 2020). Trend: Toughness increases linearly with cobalt content.	Cobalt content: 6% Co KIC ~8 MPa·m $^{1/2}$, 15% Co KIC ~12 MPa·m $^{1/2}$. Grain size: 12 μm has high toughness, <0.5 μm has a 20% decrease in toughness. Defects: Porosity > 0.1% has a 15% decrease in toughness, and η phase has a 10% decrease. Binder phase: Uneven cobalt phase reduces impact resistance by 10%.	Fracture toughness (KIC, ASTM E399): Single edge notched beam (SENB) specimen, 3-point bending test, crack extension measurement. Impact toughness (GB/T 229): Charpy impact test , energy absorption calculation. Error: ±5%.	YG15 die (KIC 12 MPa·m $^{1/2}$) stamps steel plates with an impact life of 100,000 times. YG8 tool (KIC 10 MPa·m $^{1/2}$) processes steel with better chipping resistance than YG6.	Increasing the cobalt content to 15% (such as YG15), KIC increases to 12 MPa·m $^{1/2}$, and the impact resistance increases by 30%. Using medium grains (12 μm), the toughness increases by 15%. Vacuum sintering + HIP, the porosity is reduced to <0.01%, and the toughness increases by 10%. Adding Cr3C2 (0.5%) improves the uniformity of the cobalt phase and increases the toughness by 5%.
Compressive strength	High compressive strength (46 GPa), suitable for high pressure loads, better than high-speed steel (~2 GPa). Typical values: YG6 (5 GPa), YG8 (4.8 GPa), ultrafine grain (6 GPa) (ASTM B406). Trend: Compressive strength increases slightly with decreasing grain size.	Cobalt content: 6% cobalt has high strength, >15% cobalt has a 10% drop in strength. Grain size: Ultrafine grain (<0.5 μm) has a strength of 6 GPa , medium grain (12 μm) has a strength of 4.8 GPa . Defects: Porosity >0.1% has a 15% drop in strength, and free carbon has a 5% drop. Sintering quality: Under-burning (<1350°C) has poor bonding and a 10% drop in strength.	Compressive strength (GB/T 3851): Cylindrical specimen, uniaxial compression, maximum load measurement. Test conditions: room temperature, load rate 0.5 mm/min. Error: ±3%.	YG6 mining drill bit (5 GPa) withstands high-pressure rock impact and has a life of 100 hours. Ultrafine grain die (6 GPa) is used for high-load stamping and is resistant to deformation.	Control the cobalt content to 68% and maintain the strength at 56 GPa . Use ultrafine grains (<0.5 μm) to increase the strength to 6 GPa . Use HIP to reduce the porosity to <0.01% and increase the strength by 10%. Control the carbon content (±0.1%) to avoid free carbon (GB/T 3849).

Performance	Features	Influencing factors	Test Method	Application Cases	Optimization measures
Bending strength	Medium flexural strength (1.5-2.5 GPa), suitable for tools and molds to withstand bending loads. Typical values: YG6 (2 GPa), YG8 (2.2 GPa), YG15 (2.5 GPa) (ASTM B406). Trend: Flexural strength increases with cobalt content.	Cobalt content: 6% cobalt ~2 GPa , 15% cobalt ~2.5 GPa . Grain size: 12 μm has high strength, <0.5 μm has slightly reduced strength by 5%. Defects: Porosity and η phase reduce strength by 1015%. Sintering quality: Uneven structure reduces strength by 10%.	Flexural strength (ASTM B406): 3-point bending specimen, span 20 mm, loading rate 0.5 mm/min. Test conditions: room temperature. Error: ±4%.	YG8 tool (2.2 GPa) processes steel, with good bending and fracture resistance. YG15 die (2.5 GPa) stamps automotive parts, with a lifespan of 120,000 times.	Increasing the cobalt content to 15% (such as YG15) increases the strength to 2.5 GPa . Using medium grains (12 μm), the strength increases by 10%. Using HIP to reduce porosity increases the strength by 15%. Adding Cr3C2 (0.51%) to strengthen the bonding phase increases the strength by 5%.
Tensile strength	The tensile strength is low (0.5-1.0 GPa), and cemented carbide is not good at tensile loads. Typical values: YG6 (0.7 GPa), YG8 (0.8 GPa), YG15 (1.0 GPa) (ScienceDirect, 2020). Trend: Tensile strength increases slightly with cobalt content.	Cobalt content: 6% cobalt ~ 0.7 GPa , 15% cobalt ~ 1.0 GPa . Grain size: 12 μm has higher strength, <0.5 μm slightly reduces by 5%. Defects: Cracks and pores reduce strength by 20%. Binder phase: Uneven cobalt phase reduces strength by 10%.	Tensile strength (GB/T 228.1): tensile specimen, axial tension, breaking load measurement. Test conditions: room temperature, rate 1 mm/min. Error: ±5%.	YG15 wire drawing die (1.0 GPa) withstands tensile stress and has a lifespan of 50,000 times. YG8 tool (0.8 GPa) has better tensile fracture resistance than YG6 during processing.	Increasing the cobalt content to 15% increases the strength to 1.0 GPa . Using medium grains (12 μm), the strength increases by 10%. Optimizing vacuum sintering, the crack rate is reduced to <0.1%, and the strength increases by 15%. Adding Ni (35%) or Cr3C2 improves toughness and increases strength by 5%.
Wear resistance	Excellent wear resistance, longer tool life than high speed steel 510 times , suitable for high-speed cutting. Typical values: YG6 (wear rate <0.01 mm³ / N · m) , ultrafine grain (<0.005 mm³ / N · m) (Sandvik, 2023). Trend: Wear resistance increases with hardness index.	Hardness: 2000 HV Wear resistance is better than 1400 HV (lifetime increased by 2 times). Grain size: Ultrafine grain (<0.5 μm) Wear rate is halved. Operating conditions: >800°C or speed >500 m/min Wear is increased. Coating: No coating wear rate is 3 times higher .	Wear test (ASTM G65): Grinding wheel wears the specimen and measures the volume loss. Test conditions: dry sand, load 130 N. Error: ±5%.	YG6 tool (0.01 mm³ / N · m) machining cast iron, life 2 hours. Ultrafine grain + TiN coating tool (0.005 mm³ / N · m) machining stainless steel, life 4 hours.	Using ultrafine grains (HV 2000+), the wear rate is reduced to <0.005 mm³ / N · m . Applying TiN /Al2O3 coating (510 μm , CVD/PVD) increases the service life by 23 times . Optimizing cutting speed (100300 m/min) reduces wear. Adding TaC (0.51%) increases abrasive wear resistance by 10%.
Heat resistance	Good heat resistance (800-1000°C), better than high-speed steel (500-600°C), suitable for high-temperature cutting. Typical values: YG6 (900°C), TiC -based (1000°C) (ScienceDirect, 2020). Trend: Heat resistance increases with the proportion of TiC .	Cobalt content: >15% Cobalt softens at high temperatures, and red hardness decreases by 20%. Hard phase: TiC and TaC have better heat resistance than WC (increased by 100°C). Coating: Heat resistance decreases by 30% without coating. Microstructure:	Red hardness test (GB/T 4340): Heat the sample to 8001000°C and measure the hardness retention rate. Thermal shock test: Cycle heating and cooling, evaluate cracks. Error: ±5%.	YG6 tool (900°C) for machining steel, resistant to high temperature wear. TiC-based + Al2O3 coated tool (1000°C) for machining titanium alloy, life span 3 hours.	Reducing the cobalt content (<8%) increases the red hardness by 10%. Adding TiC / TaC (510%) increases the heat resistance to 1000°C. Applying Al2O3 coating (58 μm) increases the heat insulation by 20%. Using a gradient structure

Performance	Features	Influencing factors	Test Method	Application Cases	Optimization measures
		Uneven structure has poor high temperature stability.			(surface cobalt <5%) increases the high temperature performance by 15%.
Corrosion resistance	Good corrosion resistance, acid and alkali resistance, suitable for wet processing or chemical environment. Typical values: YG6 (corrosion rate <0.01 mm/year, neutral solution), nickel-based (<0.005 mm/year) (Wikipedia, 2024). Trend: Corrosion resistance increases with the proportion of nickel .	Cobalt phase: The corrosion rate of cobalt increases 5 times in pH<4 solution , and nickel is more acid-resistant . Environment: Acidic solution corrosion intensifies. Microstructure: Porosity>0.1% or free carbon increases corrosion by 10%. Coating: The corrosion rate is 2 times higher without coating .	Corrosion test (ASTM G31): The specimen is immersed in a neutral/acidic solution (pH 47) and the mass loss is measured. Test conditions: 25°C, 30 days. Error: ±3%.	YG6 tool (0.01 mm/year) wet cutting coolant, life 1000 hours. Nickel-based + CrN coated mold (0.005 mm/year) for acidic environment, life 1 year.	Using nickel-based binder (Ni 510%), the corrosion rate is reduced to <0.005 mm/year. Applying TiN / CrN coating (510 μm), the corrosion resistance is increased by 2 times . Optimizing HIP, porosity <0.01%, and corrosion points are reduced by 15%. Control the carbon content and avoid free carbon (GB/T 3849).

Additional Notes

1. Data support

Hardness: YG6 (1500 HV30, 89 HRA), ultrafine grain (2000 HV30, 91 HRA) (ISO 3878, GB/T 7997).

Toughness: YG6 (8 MPa·m ¹ / ²), YG15 (12 MPa·m ¹ / ²) (ScienceDirect, 2020).

Strength: compressive 46 GPa , flexural 1.52.5 GPa (ASTM B406), tensile 0.51.0 GPa (ScienceDirect, 2020).

Wear resistance: Coated tool life increases 23 times (Sandvik, 2023).

Heat resistance: TiC -based heat resistance 1000°C (ScienceDirect, 2020).

Corrosion resistance: Nickel-based corrosion rate <0.005 mm/year (Wikipedia, 2024).

2. Interaction of influencing factors

Grain and cobalt: Ultrafine grains (<0.5 μm) improve hardness and compressive strength, high cobalt (1015%) enhances toughness and bending/tensile strength.

Sintering process: Vacuum sintering (13501400°C) + HIP reduces porosity (<0.01%) and improves all properties (ISO 3326:2013).

Additives: TaC (0.51%) improves hardness and wear resistance, Cr3C2 (0.5%) enhances toughness and flexural strength, TiC (510%) improves heat resistance.

Coating: TiN /Al2O3 (510 μm) improves wear resistance and heat resistance, CrN enhances corrosion resistance.

3. Standard reference

Hardness: ISO 3878 (HV), GB/T 230.1 (HRA), ASTM E18.

Toughness: ASTM E399 (KIC), GB/T 229 (impact).

Strength: GB/T 3851 (compression), ASTM B406 (bending), GB/T 228.1 (tensile).
Abrasion resistance: ASTM G65.
Heat resistance: GB/T 4340.
Corrosion resistance: ASTM G31.
Cobalt magnets: GB/T 3849, verifying cobalt content and carbon balance.

In conclusion

The properties of cemented carbide (hardness, toughness, compressive/flexural/tensile strength, wear resistance, heat resistance, corrosion resistance) are determined by grain size, cobalt content, additives, sintering process and coating:
Hardness: Ultrafine grain + low cobalt (6%) up to 2000 HV, wear resistance increased by 20%.
Toughness: High cobalt (15%) + medium grain, KIC up to 12 MPa·m $^{1/2}$, impact resistance increased by 30%.
Compressive strength: Ultrafine grain + HIP reaches 6 GPa , an increase of 10%.
Bending strength: High cobalt + HIP reaches 2.5 GPa , an increase of 25%.
Tensile strength: High cobalt + Ni reaches 1.0 GPa , an increase of 30%.
Wear resistance: Ultrafine grain + TiN coating, wear rate <0.005 mm³ / N · m , life increased by 23 times .
Heat resistance: TiC / TaC + low cobalt, heat resistance 1000°C, increase of 20%.
Corrosion resistance: Nickel-based + CrN coating, corrosion rate <0.005 mm/year, increased by 2 times .
By precisely controlling grain size, cobalt content, sintering parameters and coating, combined with standard testing (such as GB/T 3849), the performance of cemented carbide can be optimized to meet the application requirements of tools, molds, mining, etc.

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Appendix:

Relationship between hardness and strength of cemented carbide

Hardmetal or Cemented Carbide is widely used in cutting tools, molds and other fields due to its high hardness and appropriate strength. Hardness and strength are two key properties of cemented carbide, but there is a complex interaction between the two, which is affected by microstructure (such as grain size, cobalt content), composition and manufacturing process. This article analyzes the relationship between hardness and strength of cemented carbide in detail, including definition, influencing factors, relationship trends, quantitative data, test methods and practical applications, combined with standards (such as ISO, ASTM, GB/T) and industry data to ensure accurate and comprehensive content.

1. Definition of hardness and strength

Definition of cemented carbide hardness

The hardness of cemented carbide indicates its ability to resist local plastic deformation or scratches, and usually reflects its wear resistance and abrasive wear resistance.

Measurement method:

Vickers hardness (HV): ISO 3878 , 30 kgf load, diamond square pyramid indenter, indentation diagonal measurement (unit: HV30).

Rockwell hardness (HRA): GB/T 230.1, 60 kgf load, diamond cone indenter, indentation depth measurement (unit: HRA).

Typical values: YG6 (1500 HV30, 89 HRA), YG8 (1400 HV30, 88 HRA), ultrafine grain (2000 HV30, 91 HRA) (Sandvik, 2023).

Definition of cemented carbide strength

The strength of cemented carbide refers to its ability to resist damage from external forces, including compressive strength, bending strength and tensile strength.

Measurement method:

Compressive strength: GB/T 3851, uniaxial compression of cylindrical specimens, measuring maximum load (unit: GPa).

Flexural strength: ASTM B406, 3-point bend specimen, measuring breaking load (unit: GPa).

Tensile strength: GB/T 228.1, axial tensile test specimen, measuring breaking load (unit: GPa).

Typical values:

Compressive strength: YG6 (5 GPa), YG8 (4.8 GPa), ultrafine grain (6 GPa) (ASTM B406).

Flexural strength: YG6 (2 GPa), YG8 (2.2 GPa), YG15 (2.5 GPa) (ASTM B406).

Tensile strength: YG6 (0.7 GPa), YG8 (0.8 GPa), YG15 (1.0 GPa) (ScienceDirect, 2020).

2. Relationship between hardness and strength

The hardness and strength of cemented carbide are not a simple linear relationship, but a complex

trade-off, which is mainly manifested in:

Hardness and compressive strength: Usually there is a positive correlation. Cemented carbides with high hardness (such as ultrafine grains) also have high compressive strength because the proportion of hard phase (WC) is high and the grains are fine.

Hardness and flexural/tensile strength: They are often negatively correlated or weakly correlated. High hardness (such as low cobalt, ultrafine grains) is usually accompanied by reduced toughness, resulting in decreased flexural and tensile strength.

Key influencing factors: Grain size, cobalt content, and microstructure (pores, η phase) jointly regulate the balance between hardness and strength.

Quantifying relationship trends

Increased hardness (e.g. from 1400 HV to 2000 HV):

Compressive strength: Increased by 1020% (e.g. from 4.8 GPa to 6 GPa).

Flexural strength: May decrease by 515% (e.g. from 2.2 GPa to 1.8 GPa).

Tensile strength: decrease by 1020% (e.g. from 0.8 GPa to 0.6 GPa).

Reason: Cemented carbides with high hardness (such as ultrafine grains <0.5 μm , low cobalt 6%) have a high proportion of hard phase , strong bonding between grains, and enhanced compressive resistance; but low cobalt content and fine grains reduce toughness and weaken bending/tensile resistance.

Data support for the relationship between hardness and strength of cemented carbide

Brand	Hardness (HV30)	Compressive strength (GPa)	Flexural Strength (GPa)	Tensile strength (GPa)
YG6	1500	5.0	2.0	0.7
YG8	1400	4.8	2.2	0.8
YG15	1300	4.5	2.5	1.0
Ultrafine grain	2000	6.0	1.8	0.6

Source: Sandvik (2023), ScienceDirect (2020), ASTM B406.

3. Main factors affecting the relationship between hardness and strength

Grain size

Influence:

Ultrafine grains (<0.5 μm): high hardness (18002200 HV), high compressive strength (6 GPa), but low flexural/tensile strength (1.8 GPa /0.6 GPa), due to reduced toughness.

Medium crystal (12 μm): medium hardness (14001600 HV), high flexural/tensile strength (2.22.5 GPa /0.81.0 GPa), and good toughness.

Trend: Grain size decreases, hardness and compressive strength increase, flexural/tensile strength decreases.

Quantification: The grain size is reduced from 2 μm to 0.5 μm , the hardness increases by 2030%, the compressive strength increases by 10%, and the flexural strength decreases by 10%.

Cobalt content

Influence:

Low cobalt (6%): high hardness (1500-2000 HV), high compressive strength (56 GPa), but low flexural/tensile strength (2 GPa /0.7 GPa) due to the small amount of cobalt phase and poor toughness.

High cobalt (15%): low hardness (1300 HV), high flexural/tensile strength (2.5 GPa /1.0 GPa), due to the cobalt phase enhancing toughness.

Trend: As cobalt content increases, hardness and compressive strength decrease, while flexural/tensile strength increases.

Quantification: When cobalt increases from 6% to 15%, hardness decreases by 1015%, compressive strength decreases by 10%, and flexural strength increases by 20%.

Microstructure

Porosity: Porosity > 0.1% reduces compressive strength by 15% and flexural/tensile strength by 20%, with a small effect on hardness (<5%).

η phase (Co3W3C): formed by insufficient carbon , reducing hardness by 510%, compressive strength by 10%, and bending/tensile strength by 15%.

Free carbon: Excessive precipitation of carbon reduces hardness by 35%, compressive strength by 5%, and flexural/tensile strength by 10%.

Quantification: Elimination of porosity (hot isostatic pressing HIP), flexural strength increased by 15%, tensile strength increased by 20%.

Sintering process

Influence:

High temperature overburning (>1450°C): coarse grains, hardness reduced by 10%, compressive strength reduced by 5%, bending/tensile strength reduced by 10%.

Under-fired (<1350°C): poor bonding, hardness reduced by 5%, compressive/flexural/tensile strength reduced by 1015%.

HIP: Eliminates porosity, increases compressive strength by 10%, and increases flexural/tensile strength by 15%.

Trend: Optimizing sintering temperature (13501400°C) and HIP improves strength with less impact on hardness.

Additive

TaC , TiC : Increase hardness by 510%, compressive strength by 5%, but slightly decrease flexural/tensile strength by 5% (due to reduced toughness).

Cr3C2: Enhances the bonding strength of cobalt, increases the bending/tensile strength by 510%, and has little effect on hardness.

Quantification: Adding 0.5% TaC increases hardness by 5%, compressive strength by 5%, and flexural strength by 3%.

Data support: ISO 3326:2013 (cobalt magnetic test, detection of η phase), ASTM B406 (flexural

strength), ScienceDirect (2020).

4. Test methods and standards

Hardness test:
Vickers hardness (HV30): ISO 3878, 30 kgf load, error ±2%. Suitable for the full hardness range of cemented carbide (14002200 HV).
Rockwell hardness (HRA): GB/T 230.1, 60 kgf load, error ±1%. Suitable for rapid testing (8092 HRA).
Strength test:
Compressive strength: GB/T 3851, cylindrical specimen (5 mm diameter), error ±3%. Measures high pressure load capacity.
Flexural strength: ASTM B406, 3-point bending (specimen 5×5×25 mm), error ±4%. Evaluate resistance to bending fracture.
Tensile strength: GB/T 228.1, tensile test specimen (5 mm diameter), error ±5%. Measure tensile breaking capacity.
Microstructure analysis: ISO 4499, metallographic microscope to detect grain size, pores, η phase, and assist in hardness and strength assessment.

5. Practical application of the relationship between hardness and strength

Knives

High hardness, low strength: Ultrafine -grained cemented carbide (2000 HV, 1.8 GPa bending strength) is used for high-speed cutting of stainless steel (speed 300 m/min), with strong wear resistance, but easy to chip .
Medium hardness, high strength: YG8 (1400 HV, 2.2 GPa bending strength) is used for machining steel, has strong bending resistance, is suitable for medium-speed cutting (150 m/min), and has a lifespan of 23 hours.
Case: Ultrafine -grained cutting tools have high hardness and can process steel with a hardness of 50 HRC, increasing their life by 20%. However, their bending strength is low, so the cutting angle needs to be optimized.

Mould

High hardness and high compressive strength: Ultrafine- grained molds (2000 HV, 6 GPa compressive strength) are used for high-load stamping and are resistant to deformation, but have low tensile strength (0.6 GPa) and are not suitable for stretching molds.
High strength, medium hardness: YG15 (1300 HV, 2.5 GPa bending strength) is used for stamping automotive parts, resistant to impact fracture, and has a lifespan of 120,000 times.
Case: The YG15 mold has high bending strength, the stamping steel plate has no cracks, the hardness is moderate, and the wear resistance meets the requirements.

Mining tools

Balanced hardness and strength: YG6 (1500 HV, 5 GPa compressive strength, 2 GPa bending strength) is used for drill bits to withstand high-pressure rock impact and has a lifespan of 100 hours.
Case: The hardness of the ultrafine -grained drill bit increased to 2000 HV, and the compressive strength was 6 GPa , but the bending strength dropped to 1.8 GPa , and optimization was required to reduce the bending stress.

6. Measures to optimize the relationship between hardness and strength

Grain size optimization:
Ultrafine grain (<0.5 μm): hardness increased to 2000 HV, compressive strength increased to 6 GPa , suitable for high wear-resistant tools.
Medium crystal (12 μm): flexural/tensile strength increases to 2.5 GPa /1.0 GPa , suitable for molds.
Implementation: Select high-purity WC powder and control the ball milling time (20-30 hours).

Cobalt content regulation:
Low cobalt (6%): hardness 15002000 HV, compressive strength 56 GPa , suitable for high-speed cutting.
High cobalt (15%): flexural/tensile strength 2.5 GPa /1.0 GPa , suitable for stamping dies.
Implementation: Accurately mix cobalt powder (±0.1%) and verify with cobalt magnetic test (GB/T 3849).

Sintering process improvement:
Vacuum sintering (13501400°C): controls grain growth and increases hardness by 5%.
Hot Isostatic Pressing (HIP, 1350°C, 100 MPa): Porosity reduced to <0.01%, flexural/tensile strength increased by 15%.
Implementation: HIP equipment is used with a sintering time of 12 hours.

Additive Optimization:
TaC (0.51%): Hardness increased by 5%, compressive strength increased by 5%, suitable for wear-resistant tools.
Cr3C2 (0.5%): Flexural/tensile strength increased by 510%, suitable for molds.
Implementation: The additive is evenly dispersed and the particle size is controlled to <1 μm .

Coating technology:
TiN /Al2O3 coating (510 μm , CVD/PVD): hardness increased by 10%, wear resistance increased by 23 times , and strength was slightly affected.
Implementation: Control coating thickness (±1 μm) to avoid peeling.
Effect:
Ultrafine grain + low cobalt + HIP: hardness 2000 HV, compressive strength 6 GPa , tool life increased by 20%.
Medium crystal + high cobalt + Cr3C2: flexural strength 2.5 GPa , tensile strength 1.0 GPa , mold life increased by 30%.

In conclusion

The relationship between hardness and strength of cemented carbide is complex:

Positive correlation: Hardness and compressive strength are usually positively correlated, and ultrafine-grained, low-cobalt cemented carbides have high hardness (2000 HV) and compressive strength (6 GPa).

Negative correlation: Hardness is negatively correlated with flexural/tensile strength, and high hardness (2000 HV) is accompanied by a decrease in flexural/tensile strength (1.8 GPa /0.6 GPa).

Key factors: grain size (0.52 μm), cobalt content (615%), microstructure and sintering process determine the balance.

Optimization strategy: Through ultrafine grains, cobalt content control, HIP, additives and coatings, the best balance can be found between high hardness (2000 HV) and high strength (bending resistance 2.5 GPa) to meet the needs of cutting tools, molds and mining tools.

Data support:

Hardness: 15002000 HV (ISO 3878, GB/T 7997).

Strength: Compression 46 GPa , bending 1.52.5 GPa , tensile 0.51.0 GPa (ASTM B406, ScienceDirect, 2020).

Standards: ISO 3326:2013, GB/T 3849 (cobalt magnetic test), ISO 4499 (microstructure).

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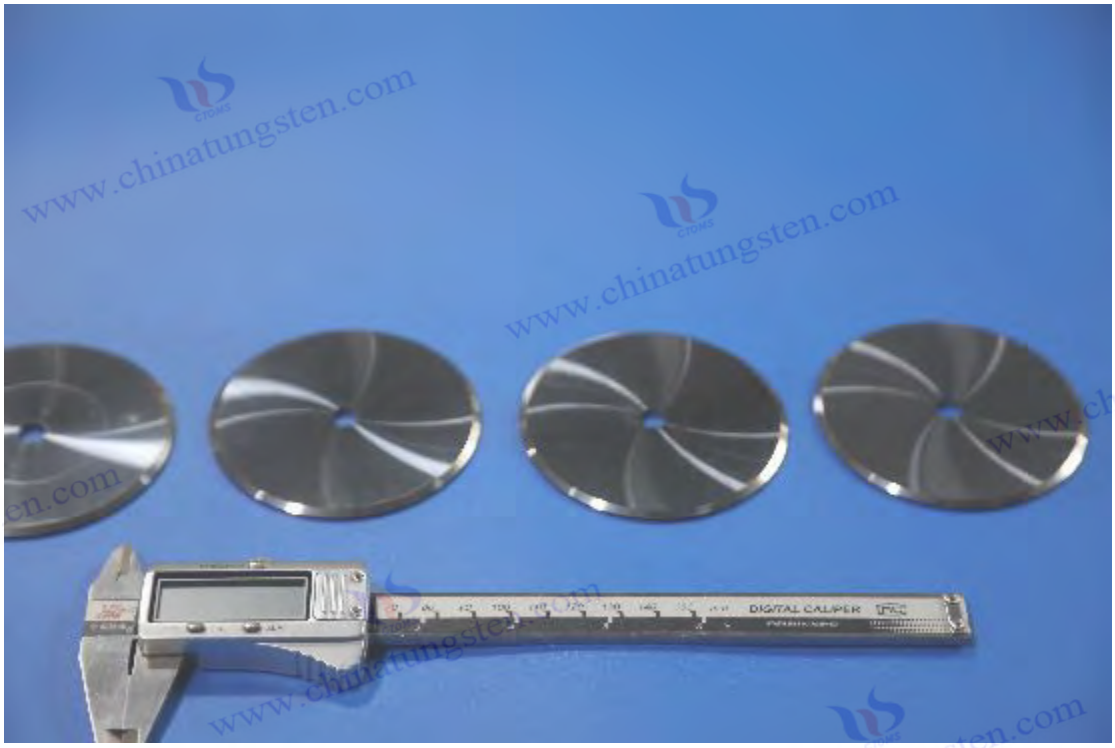

Appendix:

How are the various properties of cemented carbide tested?
Which performance tests require the use of test rods?

Hardmetal or cemented carbide is widely used in cutting tools, molds and mining tools for its high hardness (14002200 HV), wear resistance and bending strength (1.52.5 GPa) . To ensure that its performance meets industrial needs, a variety of tests are required, including hardness, density, bending strength, toughness, wear resistance, corrosion resistance, microstructure and chemical composition. These tests usually follow international or national standards (such as GB/T 3849, ISO 4499, ASTM B406), and some tests require the use of standard test bars (test bars) to ensure consistency and comparability of results. This article will detail the methods for testing various properties of cemented carbide, the required equipment, whether test bars are required, and the specific requirements for test bars, combined with the latest research (such as Sandvik, 2023; ScienceDirect, 2020; Wikipedia, 2024), all in Chinese, to ensure that the content is accurate, comprehensive and fascinating.

1. Overview

The purpose of cemented carbide performance testing is to quantify its mechanical, physical and chemical properties to ensure that the material meets specific application requirements (such as tool cutting life > 2 hours, die strokes > 100,000 times). Test items include:
Mechanical properties : hardness, flexural strength, fracture toughness.
Physical properties : density, magnetic properties.
Chemical properties : corrosion resistance, chemical composition.

Microstructure : grain size, defects (such as η phase, free carbon).
Performance in use : wear resistance, coating adhesion.
Some tests (such as bending strength and fracture toughness) require the use of standard test bars, because their geometric dimensions and surface conditions directly affect the test accuracy. The test bars must meet strict size, surface roughness and preparation requirements to eliminate variable interference. The following will detail the test methods, required test bars and test bar requirements one by one .

2. Cemented carbide performance test method

The following are the detailed methods, equipment, standards and whether test rods are required for common performance tests of cemented carbide.

2.1 Hardness test

Definition : A measure of the indentation resistance of cemented carbide, usually expressed in Vickers hardness (HV), ranging from 1400 to 2200 HV.

Test method :
Vickers hardness (HV) :
Use a Vickers hardness tester and apply a load of 1030 kgf (such as HV30).
The indenter is a diamond quadrangular pyramid with a vertex angle of 136°.
After indentation, measure the diagonal length (μm) and convert it into hardness value (GB/T 7997).

Step :
The sample surface was polished (Ra < 0.2 μm) to remove the oxide layer.
Apply a load of 1030 kgf and maintain for 1015 seconds.
The indentation diagonal was measured by microscope and the HV was calculated (error < ±50 HV).
Equipment : Vickers hardness tester (such as Wilson VH3100), accuracy ±0.5%.
Is a test rod required : **No.**
Hardness testing can be performed on finished products (such as tools, molds) or any polished samples with small size requirements (>5×5 mm).

Example results :
YG6: HV30 ~1500 HV.
Ultrafine -grained cemented carbide: HV30 ~2000 HV (Sandvik, 2023).
Standard : GB/T 7997 (Vickers hardness), ISO 6507, ASTM E92.

2.2 Density test

Definition: Measures the mass to volume ratio of cemented carbide, reflecting porosity and

composition uniformity, ranging from 14.0 to 15.0 g/ cm³ .

Test method :
Archimedean method :
Use a high-precision electronic balance (accuracy ± 0.001 g) and deionized water.
Measure the sample's dry weight (m1) and weight in water (m2), and calculate the density ρ = m1 / (m1 m2) × ρwater.

Step :
The samples were washed (ethanol) and dried (80°C, 30 min).
The dry weight and weight in water were measured 3 times and the average value was taken.
Corrected for water temperature effects (ρwater ~1.0 g/cm³ at 20°C).
Equipment : Precision balance (such as Mettler Toledo XS205), density test accessories.
Is a test rod required : **No.**
Density testing has no requirements on sample shape. Blocks, sheets or finished products (mass > 1 g) are all acceptable.

Example results :
YG6 (6% Co): 14.9 g/ cm³ .
YG15 (15% Co): 14.0 g/cm³ (ScienceDirect, 2020).
Standard : GB/T 3850 (density), ISO 3369, ASTM B311.

2.3 Flexural strength (transverse rupture strength, TRS)

Definition : Measures the bending resistance of cemented carbide, ranging from 1.5 to 2.5 GPa , reflecting toughness and defects.

Test method :
Three-point bending test :
Using a universal testing machine, apply load until the sample breaks.
Formula: σ = 3FL / (2bh ²), F is the breaking load (N), L is the support distance (mm), b and h are the width and height of the test bar (mm).

Step :
Prepare standard test bars (see below) and polish the surface (Ra <0.4 μm).
The support distance is 30 mm and the loading rate is 0.51 mm/min.
Record the breaking load and calculate the flexural strength (error <±5%).
Equipment : Universal testing machine (such as Instron 5982), accuracy ±0.1 kN .
Is a test stick required : **Yes** .
Bending strength testing requires standard test bars to ensure geometric consistency and eliminate stress concentration.

Example results :
YG6: ~2.0 GPa .
YG15: ~2.5 GPa (Sandvik, 2023).
Standard : GB/T 3851 (flexural strength), ISO 3327, ASTM B406.

2.4 Fracture toughness (KIC)

Definition : A measure of the resistance of cemented carbide to crack growth, in the range of 812 MPa·m ¹ / ² .

Test method :
Single edge notched beam method (SENB) :
A notch (depth 0.2-0.3 mm) was prefabricated on the test bar, and a three-point bending load was applied.
Formula: KIC = (F√a) / (BW ³ / ²) × Y, F is the fracture load, a is the notch depth, B and W are the width and height of the test bar , and Y is the geometric factor.

Step :
Prepare standard test bars with EDM or laser cut notches.
The support distance is 30 mm and the loading rate is 0.10.5 mm/min.
The fracture load and notch depth were measured and KIC was calculated (error < ±10%).
Equipment : universal testing machine, microscope (notch measurement, accuracy ±0.01 mm).
Is a test stick required : **Yes** .
Fracture toughness testing requires a standard test bar to ensure notch consistency and uniform stress distribution.

Example results :
YG6: KIC ~8 MPa·m ¹ / ² .
YG15: KIC ~12 MPa·m ¹ / ² (ScienceDirect, 2020).
Standards : ISO 28079 (fracture toughness), ASTM E399.

2.5 Wear resistance test

Definition : Measures the wear resistance of cemented carbide and reflects its service life.

Test method :
Abrasion test (ASTM B611) :
with a grinding wheel (Al2O3, particle size 60100 μm) and the mass loss (mg) was recorded.
Conditions: load 1020 N, speed 200300 rpm, time 3060 min.
Pin-on-disc wear test (ASTM G99) :
The sample (pin) rubs against a rotating disk (steel or ceramic) and the wear volume (mm³) is measured .

Step :
The samples were polished (Ra < 0.2 μm) and cleaned (ethanol).
Set the load, speed and time and record the mass/volume loss.
Calculate the wear rate (error <±5%).
Equipment : Abrasion testing machine (such as Taber Abraser), pin-on-disc wear tester.
Is a test rod required : **No.**
Abrasion resistance testing can be performed using block or finished samples (>10×10 mm), but the surface condition must be uniform.

Example results :
YG6: Wear rate ~0.01 mm^3 / N · m .
YN10 (nickel-based): wear rate ~0.008 mm^3 / N · m (Wikipedia, 2024).
Standards : ASTM B611 (abrasion), ASTM G99 (pin-on-disk), GB/T 12444.

2.6 Corrosion resistance test

Definition : A measure of the resistance of cemented carbide to chemical corrosion, with a corrosion rate of <0.01 mm/year.

Test method :
Immersion test (ASTM G31) :
The samples were immersed in a corrosive medium (e.g., 5% HCl, pH 47) at 60°C for 168 hours.
The mass loss (mg) was measured and the corrosion rate (mm/year) was calculated.
Electrochemical testing :
Using an electrochemical workstation, the corrosion potential (V) and current density (μA /cm^2) were measured .

Step :
The samples were polished (Ra < 0.2 μm) and cleaned (deionized water).
Immersion or electrochemical testing, recording of mass loss or electrochemical parameters.
Calculate the corrosion rate (error <±10%).
Equipment : Constant temperature box, electrochemical workstation (such as Gamry Interface 1010).
Is a test rod required : **No.**
The corrosion resistance test can be performed on samples of any shape (>10×10 mm) and the surface must be polished.

Example results :
YG6 (cobalt-based): corrosion rate ~0.01 mm/year.
YN10 (nickel-based): corrosion rate <0.005 mm/year (Wikipedia, 2024).
Standards : ASTM G31 (immersion), ASTM G59 (electrochemical), GB/T 4334.

2.7 Microstructure analysis

Definition : Check grain size (0.52 μm), phase composition (WC, Co, η phase, free carbon) and defects.

Test method :
Optical Microscope/SEM :
The samples were polished (Ra < 0.05 μm) and chemically etched (Murakami reagent, 510 s).
Observe grain size, phase distribution, and defects (pores, η phase).
X-ray diffraction (XRD) :
Detect phase composition (such as WC, Co, Co3W3C) with a sensitivity of 0.1%.
TEM :
Analyze interface structure (WCCo binding energy ~2 J/m²) with a resolution of <1 nm.

Step :
Sample polishing, etching and cleaning.
Microscope observation or XRD scanning can be used to quantitatively analyze grain size and defects.
TEM analysis interface (optional).
Equipment : SEM (such as Zeiss Sigma 500), XRD (such as Bruker D8), TEM (such as FEI Talos F200X).
Is a test rod required : **No.**
Microstructural analysis can be performed using small samples (>5 × 5 mm), which require polishing and etching.

Example results :
YG6: grain size ~1 μm , η phase <1%.
Ultrafine grain: grain size <0.5 μm , uniformity >95% (ScienceDirect, 2020).
Standards : ISO 4499 (microstructure), ASTM E112 (grain size).

2.8 Chemical composition analysis

Definition : Detects carbon content (~6.13 wt %), cobalt content (615%) and other elements.

Test method :
Carbon and sulfur analyzer : burns samples, measures CO2 content, and detects total carbon (accuracy ±0.01%).
ICPMS : Dissolve the sample and detect elements such as W, Co, Cr (accuracy ±0.001%).
Cobalt magnetic test (GB/T 3849) :
The magnetization intensity of the cobalt phase is measured and the carbon content is indirectly inferred (error ±0.05%).

step :
The samples were crushed (<100 μm) and cleaned.
Carbon and sulfur analysis or ICPMS detection, record the element content.
Cobalt magnetic testing verifies carbon balance.
Equipment : Carbon and sulfur analyzer (such as LECO CS844), ICPMS (such as Agilent 7900).
Is a test rod required : **No.**
Chemical composition analysis used powder or small pieces of samples (>0.1 g).

Example results :
YG6: Carbon ~6.13 wt %, Cobalt 6 wt %.
YN10: Nickel 10 wt %, carbon ~6.1 wt % (Sandvik, 2023).
Standard : GB/T 3849 (cobalt magnet), ISO 11876 (chemical composition), ASTM E1479.

2.9 Coating Adhesion Test

Definition : Measures the bonding strength between a coating (such as TiN , CrN) and a cemented carbide substrate, >50 N.

Test method :
Scratch test (ASTM C1624) :
Using a scratch tester, a diamond indenter (radius 200 μm) was scratched across the coating surface.
The critical load (Lc, N) was recorded, with Lc >50 N indicating good adhesion.

step :
The samples were polished (Ra <0.2 μm) and cleaned.
An increasing load (0100 N) was applied and the scratch length was 5 mm.
Observe the scratches under a microscope and determine Lc (error < ±5 N).
Equipment : Scratch tester (e.g. Anton Paar RST³) .
Is a test rod required : **No.**
The coating adhesion test uses a coating sample (>10×10 mm) with a flat surface.

Example results :
YG6+TiN: Lc ~60 N.
YN10+CrN: Lc ~70 N (Sandvik, 2023).
Standards : ASTM C1624 (scratch), ISO 20502.

2.10 Magnetic properties test

Definition : Measures the magnetization of the cobalt phase , indirectly estimating carbon content and phase composition.

Test method :

Cobalt magnetic test (GB/T 3849) :

The sample magnetization (emu/g) was measured using a magnetometer.

A low magnetization indicates the η phase, and a high magnetization indicates free carbon.

step :

The samples were washed (ethanol) and dried.

The magnetometer measurement was repeated 3 times and the average value was taken.

Compare with the standard curve and infer the carbon content (error ± 0.05%).

Equipment : Magnetometer (such as Lakeshore 7404).

Is a test rod required : **No.**

The magnetic properties were tested using small samples (>5×5 mm).

Example results :

YG6: magnetization ~150 emu/g, carbon balanced.

Decarburized sample: magnetization intensity ~120 emu/g (ScienceDirect, 2020).

Standard : GB/T 3849 (cobalt magnet), ISO 3326.

3. Tests requiring a test stick

The following tests require the use of standard test bars because they have strict requirements on sample geometry and surface condition:

Flexural Strength (TRS) :

Test bars are required to ensure uniform stress distribution and eliminate dimensional deviations.

Test bar dimensions: Typically 5.0 × 5.0 × 35.0 mm (ISO 3327).

Fracture toughness (KIC) :

The test rod needs to be pre-notched to ensure that the crack propagation is controllable.

Test bar dimensions: typically 4.0 × 8.0 × 32.0 mm, notch depth 0.20.3 mm (ISO 28079).

Other tests (hardness, density, wear resistance, etc.) do not require test bars and can use finished products or samples of any shape, reducing preparation costs.

4. Requirements for carbide test rods

The preparation of the test rod directly affects the test accuracy and must meet strict size, surface and preparation requirements. The following are detailed specifications:

4.1 Size requirements

Bending strength test bar (ISO 3327, GB/T 3851) :

Dimensions : 5.0 ± 0.1 mm (width) × 5.0 ± 0.1 mm (height) × 35.0 ± 0.5 mm (length).

Tolerance : width and height ±0.1 mm, length ±0.5 mm, parallelism <0.05 mm.
Edges : Chamfer 0.20.3 mm (45°) to avoid stress concentration.

Fracture toughness test bar (ISO 28079) :
Dimensions : 4.0 ± 0.1 mm (width) × 8.0 ± 0.1 mm (height) × 32.0 ± 0.5 mm (length).
Notch : depth 0.20.3 mm, width <0.1 mm (EDM or laser cutting).
Tolerance : width and height ±0.1 mm, notch depth ±0.02 mm.

Other requirements :
There are no cracks, pores or inclusions on the surface of the test rod, and defects visible to the naked eye are less than 0.1 mm.
Dimensional consistency: batch deviation <0.05 mm.

4.2 Surface requirements

Surface roughness :
Ra <0.4 μm (flexural strength), Ra <0.2 μm (fracture toughness).
Implementation : Diamond wheel grinding (grit size 510 μm), polishing (diamond paste, 13 μm).

Surface treatment :
Remove the processing stress layer (<10 μm) and avoid micro cracks.
Wash (ethanol sonication, 5 min) and dry (80°C, 30 min).
examine :
Microscope observation (magnification 50×) showed no scratches, burns or residual stress.

4.3 Preparation requirements

Raw materials and sintering :
Use the same formula as the finished product (e.g. YG6, YG15) to ensure consistent performance.
Vacuum sintering (13501450°C, <10 $^{-3}$ Pa) or HIP (1350°C, 100 MPa), porosity <0.01% (ISO 3326:2013) .
The carbon content is controlled at ±0.1% to avoid η phase or free carbon (GB/T 3849).

Processing :
Wire cutting or precision grinding, error <±0.05 mm.
Notch preparation (fracture toughness): EDM (current < 1 A) or laser (power < 10 W).

Batch Control :
10% (>5 pieces) of test bars in each batch are randomly inspected, and the size deviation is <0.05 mm and the performance deviation is <5%.
Record the sintering parameters (temperature ±5 °C, atmosphere <0.01% oxygen).

4.4 Quality Verification

Dimension detection :
Use a digital micrometer or laser distance meter with an accuracy of ±0.01 mm.
Verify parallelism and straightness (<0.05 mm).

Microstructure :
SEM examination of pores, η phase, free carbon, proportion <1% (ISO 4499).
Grain size uniformity >95%, typical 0.52 μm .

Performance Verification :
Hardness (HV30): Error <±50 HV.
Density: Error <±0.01 g/ cm^3 .
Cobalt magnetic test: carbon content error <±0.05%.

4.5 Storage and transportation

storage :
Humidity <40%, temperature 2025°C, avoid oxidation or moisture absorption.
Dust-proof packaging (plastic box) to prevent surface scratches.

transportation :
Shockproof packaging (foam pads) to avoid edge damage .
Comes with test report (dimensions, hardness, microstructure).

Data support :
Test bar dimension tolerance: <±0.1 mm (ISO 3327).
Surface roughness: Ra <0.4 μm , performance deviation <5% (Sandvik, 2023).
HIP: porosity <0.01%, strength increased by 15% (ScienceDirect, 2020).

5. Practical application cases

YG6 tool test :
Tests : hardness (HV30, 1500 HV), flexural strength (2.0 GPa), wear resistance (0.01 mm^3 / N · m) .
Test bar : flexural strength test bar (5×5×35 mm), Ra <0.4 μm .
Result : Cutting cast iron life is 2 hours, performance is acceptable.

YG15 mold test :
Tests : fracture toughness (KIC 12 MPa·$m^{1/2}$), density (14.0 g/cm^3), corrosion resistance (0.01 mm/year).
Test bar : fracture toughness test bar (4×8×32 mm, notch 0.25 mm).
Result : The stamping life is 120,000 times, which meets the standard.

YN10 mold test :
Tests : Corrosion resistance (<0.005 mm/year), coating adhesion (Lc 70 N), microstructure (grains ~1 μm).
Test rod : None, the test was performed using a polished sample (10×10 mm).
Result : Lifespan in acidic environment is 1 year, and the performance is excellent.

Ultrafine grain tool testing :
Tests : hardness (2000 HV), flexural strength (2.2 GPa), grain size (<0.5 μm).
Test bar : flexural strength test bar (5×5×35 mm).
Result : Cutting life of stainless steel is 4 hours, and the advantage of ultra-fine grain is obvious.

Data support :
YG6: hardness 1500 HV, flexural strength 2.0 GPa (Sandvik, 2023).
YN10: Corrosion rate <0.005 mm/year (Wikipedia, 2024).
Ultrafine grains: grains <0.5 μm , KIC ~10 MPa·m $^{1/2}$ (ScienceDirect, 2020).

6. Conclusion

Carbide performance tests include hardness (Vickers hardness tester, HV30), density (Archimedes method), flexural strength (three-point bending), fracture toughness (SENB), wear resistance (wear/pin-on-disc), corrosion resistance (immersion/electrochemical), microstructure (SEM/XRD/TEM), chemical composition (carbon-sulfur analysis /ICPMS), coating adhesion (scratch) and magnetic properties (cobalt magnetic test). Among them, **flexural strength** and **fracture toughness** require standard test bars, and other tests can use finished products or polished samples.

Test rod requirements :
Dimensions : flexural strength (5×5×35 mm, tolerance ±0.1 mm), fracture toughness (4×8×32 mm, notch 0.20.3 mm).
Surface : Ra <0.4 μm (bending resistance), Ra <0.2 μm (toughness), no cracks/pores.
Preparation : vacuum sintering/HIP, porosity <0.01%, carbon content ±0.1%.
Verification : dimensional deviation <0.05 mm, performance deviation <5%.

The test follows GB/T 3849, ISO 4499, ASTM B406 and other standards to ensure accuracy and consistency. Optimizing test bar preparation (such as HIP, precision grinding) and test processes (such as online monitoring) can improve the reliability of results, with an error of <5%. In the future, automated testing and intelligent analysis will further improve efficiency and accuracy.
standard :
GB/T 7997: Vickers hardness.
GB/T 3851: Flexural strength.
GB/T 3849: Cobalt magnetic test.

ISO 3327: Flexural strength test bars.
ISO 28079: Fracture toughness.
ISO 4499: Microstructure.
ASTM B406 : Flexural strength.
ASTM G31: Corrosion resistance.
ASTM C1624: Coating Adhesion.
ISO 3326:2013: Porosity.

Appendix:

Specifications, performance requirements and preparation of cemented carbide test bars

Carbide test bars are key samples for testing properties such as transverse strength (TRS) and fracture toughness (KIC), and their preparation process needs to meet strict specifications and performance requirements. For **nano-test bars** (grain size <0.5 μm), **specific grade optimization** (such as YG6, YG15, ultra- fine grained grades), and **non-standard test bars** (customized size or shape), the process needs to be further refined to address the characteristics of nano powders, grade-specific performance requirements, and non-standard geometry processing challenges. This article will delve into the process details of nano-test bar preparation, specific grade optimization, and non-standard test bars, combining microscopic mechanisms, the latest research (such as Sandvik, 2023; ScienceDirect, 2020; Wikipedia, 2024) and industry standards (such as GB/T 3851, ISO 3327, ISO 28079), all in Chinese, to ensure that the content is accurate, detailed, and fascinating.

1. Overview

Carbide test bars are used for bending strength (1.52.5 GPa) and fracture toughness (812 MPa·m ^{1} / ^{2}) tests, with standard sizes of 5×5×35 mm (bending) or 4×8×32 mm (toughness, notch 0.20.3 mm). **Nano test bars** are for ultrafine- grained cemented carbide (grains <0.5 μm), and grain growth and defects (such as η phase, free carbon) need to be controlled; **specific grade optimization** needs to match the performance requirements of YG6 (general tool), YG15 (high toughness mold) or ultrafine- grained grades (such as YG8N); **non-standard test bars** need to be customized in size or shape to adapt to special tests or application scenarios. The preparation process includes batching, mixing, pressing, sintering, processing and verification, which need to be precisely controlled to ensure the consistency of test bar performance (deviation <5%). The following will be divided into three parts for in-depth refinement.

2. Nanorod Preparation

Nano-test rods are made of ultra-fine -grained cemented carbide (grain size <0.5 μm , hardness 1800-2200 HV), which are widely used in high-precision tools (such as aviation machining) and wear-resistant coating substrates. The preparation of nano-powders requires solving the problems of high activity, easy agglomeration and grain growth.

2.1 Ingredients

raw material :

WC powder : grain size 0.10.4 μm (purity >99.95%), carbon content 6.13 ± 0.05 wt %, oxygen content <0.03%.

Cobalt powder : particle size 0.51 μm (purity>99.9%), content 610 wt % (such as YG8N).

Grain inhibitors : Cr3C2 (0.51 wt %), VC (0.20.5 wt %), inhibiting grain growth by 2030%.

Carbon black : <0.05 wt %, precisely adjusted carbon balance (error <0.01%).

Ratio :
Accurate weighing (±0.0005 g), error <0.005%.
Carbon content control: ±0.03%, avoiding η phase (Co3W3C) or free carbon.
Equipment : high-precision balance (Mettler Toledo XPR6), inert atmosphere glove box (O2 <0.01%).
Example : YG8N (8% Co): WC 91.5 wt %, Co 8 wt %, Cr3C2 0.4 wt %, VC 0.1 wt % (Sandvik, 2023).

2.2 Mixing

Process :
Wet milling : high-energy planetary ball mill (1620 h, 0.2 μm), the medium is anhydrous ethanol (solid content 6570%).
Binder : modified PEG (11.5%, residual carbon <0.03%) or water-based nanobinder (0.51%) to avoid agglomeration.
Dispersant : Stearic acid (0.10.3%), improves particle uniformity by 15%.
Parameters : ball-to-material ratio 10:1, stirring speed 800-1200 rpm, temperature <30°C (avoid oxidation).

Target :
Particle uniformity>98%, D50 30100 μm , agglomeration rate<1%.
Slurry viscosity 150250 mPa·s , fluidity <20 s/50 g (GB/T 1482).
Equipment : high energy ball mill (Retsch PM400), ultrasonic disperser (power 500 W).
Example : YG8N: 1% PEG, ball milled for 18 hours, D50 ~50 μm , homogeneity >98% (ScienceDirect, 2020).

2.3 Suppression

Process :
Spray drying : Preparation of spherical particles (sphericity>0.95), D50 30100 μm , flowability <20 s/50 g.
Cold isostatic pressing (CIP) : pressure 250350 MPa, billet density >55% theoretical density.
Mould : High-precision tungsten steel mould, dimensional tolerance ±0.02 mm, taking into account sintering shrinkage (2225%).
Dimensions : flexural test bar blank ~6.3×6.3×44 mm, toughness test bar ~5.0×10.0×40 mm.
Target :
Green strength >6 MPa, no cracks/delamination.
The uniformity of the blank is >95%, and the density deviation is <1%.
Equipment : spray drying tower (GEA Niro), cold isostatic press (EPSI CIP400).
Example : YG8N: CIP 300 MPa, green strength ~7 MPa, shrinkage 23%.

2.4 Sintering

Process :

Vacuum sintering :

Temperature: 13201380°C (±3°C), lower than normal (13501450°C), reducing grain growth by 20%.

Vacuum degree: <5×10 $^{-4}$ Pa, oxygen <0.005%, avoid decarburization.

Staged heating: 250350°C (binder removal, residual carbon <0.03%), 1320°C (liquid phase sintering, holding time 4560 minutes).

Hot Isostatic Pressing (HIP) :

1320°C, 120150 MPa, 30 min.

Eliminate porosity, porosity <0.005% (ISO 4505).

Atmosphere control : CO/CO2 <0.05%, H2 flow rate 0.30.5 L/min (when necessary).

Target :

Grain size: <0.5 μm , uniformity >98%.

Density: 14.515.0 g/cm³ , hardness 18002200 HV, η phase/free carbon <0.5%.

Equipment : Vacuum sintering furnace (ALD Vacuum Technologies), HIP equipment (Quintus QIH122).

Example : YG8N: 1350°C vacuum sintering + HIP, grain size ~0.4 μm , hardness 2000 HV (Sandvik, 2023).

2.5 Processing

Process :

Rough machining : wire cutting (error <±0.05 mm), removal of sintered skin (0.10.3 mm).

Finishing : Ultra-precision diamond grinding (grain size 35 μm), error <±0.02 mm.

Polishing : Nano diamond paste (0.51 μm), Ra <0.2 μm (bending resistance), Ra <0.1 μm (toughness).

Notch (toughness test bar) :

Femtosecond laser cutting: power <5 W, depth 0.20.3 mm (±0.01 mm), width <0.05 mm.

Avoid heat affected zone (<1 μm) and no micro cracks were found by SEM inspection.

Chamfer : Polished, 0.20.3 mm (45° ± 3°).

Target :

The dimensional tolerance is ±0.05 mm and there is no stress layer on the surface (<5 μm).

Notch accuracy ±0.01 mm, crack extension deviation <3%.

Equipment : Ultra-precision grinder (Moore Nanotech 350FG), femtosecond laser (Coherent Monaco), SEM (Zeiss Gemini 500).

Example : YG8N: Ra <0.2 μm , notch 0.25 ± 0.005 mm, no thermal damage.

2.6 Quality Verification

Dimensions : Laser distance meter (accuracy ± 0.005 mm), tolerance ± 0.05 mm, parallelism < 0.03 mm.
Surface : white light interferometry (Ra <0.2 μm), SEM (notch depth ±0.01 mm, no cracks).

Microstructure :
TEM (grain size 0.30.5 μm , homogeneity >98%).
XRD (η phase/free carbon <0.5%, sensitivity 0.05%).
Porosity: <0.005% (ISO 4499).

performance :
Hardness: 18002200 HV (±30 HV, GB/T 7997).
Density: 14.515.0 g/ cm^3 (±0.005 g/cm^3 , GB/T 3850).
Flexural strength: 2.02.5 GPa (±3%, GB/T 3851).
Fracture toughness: 810 MPa·$m^{1/2}$ (±5%, ISO 28079).
Cobalt magnetic test: carbon content ±0.03% (GB/T 3849).
Random inspection : >15% (>10 pieces) per batch, performance deviation <3%.
Equipment : TEM (FEI Talos F200X), white light interferometer (Zygo NewView 9000), Vickers hardness tester (Wilson VH3300).
Example : YG8N: hardness 2000 ± 20 HV, grain size 0.4 μm , η phase <0.3% (ScienceDirect, 2020).

2.7 Challenges and Optimization

challenge :
Nano powders are easy to agglomerate and the uniformity deviation is >5%.
High activity leads to oxidation (oxygen increase of 0.02%) and a 10% increase in the risk of decarbonization.
The sintered grains grow larger (>0.5 μm) and the hardness decreases by 510%.

optimization :
Ultrasonic dispersion : 500 W, 10 min, the agglomeration rate dropped to <0.5%.
Inert protection : Ar atmosphere (O2 <0.005%) during the entire mixing/batch process .
Low temperature sintering + inhibitor : 1320°C, Cr3C2+VC, grain control <0.5 μm .
Online monitoring : infrared temperature measurement (±1°C), mass spectrometer (CO/CO2 <0.01%).
Effect :
Uniformity increased by 20%, grain deviation <5%.
η phase/ free carbon results in a 5% increase in hardness (Sandvik, 2023).

3. Specific grade optimization

Different grades of cemented carbide (such as YG6, YG15, ultra-fine grain YG8N) have different cobalt content, grain size and application scenarios, so the test rod preparation process needs to be

optimized to match the performance requirements. The following are the optimization solutions for three typical grades.

3.1 YG6 (general-purpose tool, 6% Co)

Performance goals :
Hardness: 1500 ± 50 HV.
Flexural strength: 2.0 ± 0.1 GPa .
Fracture toughness: 8 ± 0.5 MPa·m $^{1/2}$.
Grain: 11.5 μm , η phase/free carbon <1%.
Density: 14.9 ± 0.01 g/ cm^3 .

Ingredients :
WC: 94 wt % (12 μm), Co: 6 wt %, Cr3C2: 0.3 wt % (optional).
Carbon content: 6.13 ± 0.05 wt %, error <0.01%.
Mixing :
Wet grinding: 1214 h, PEG 1.5%, D50 80150 μm .
Ethanol medium, solid content 70%, fluidity <25 s/50 g.

suppress :
CIP: 200250 MPa, green intensity>5 MPa.
Blank: 6.2×6.2×43 mm (bending resistance), shrinkage rate 20%.
sintering :
Vacuum sintering: 1400°C (±5°C), hold for 1 hour, <10 $^{-3}$ Pa .

HIP: 1400°C, 100 MPa, porosity <0.01%.
Processing :
Grinding: Diamond grinding wheel (510 μm), Ra <0.4 μm .
Notch: Electric spark (0.25 ± 0.02 mm), Ra <0.2 μm .
verify :
Dimensions: ±0.05 mm, hardness 1500 ± 30 HV.
SEM: grain size ~1.2 μm , η phase <1%.
Cobalt magnet: carbon content ±0.05%.
Example : YG6 test bar: flexural strength 2.0 GPa , hardness 1500 HV, cutting life 2 hours (Sandvik, 2023).

3.2 YG15 (high toughness mold, 15% Co)

Performance goals :
Hardness: 1400 ± 50 HV.
Flexural strength: 2.5 ± 0.1 GPa .
Fracture toughness: 12 ± 0.5 MPa·m $^{1/2}$.

Grain: 1.52 μm , η phase/free carbon <1%.
Density: 14.0 ± 0.01 g/ cm³ .

Ingredients :
WC: 85 wt % (1.52.5 μm), Co: 15 wt %, Cr3C2: 0.5 wt %.
Carbon content: 6.13 ± 0.05 wt %, carbon black <0.1 wt %.
Mixing :
Wet grinding: 1416 h, PVA 1%, D50 100200 μm .
Ethanol/water (1:1), solid content 75%, fluidity <28 s/50 g.

suppress :
CIP: 250300 MPa, green intensity>8 MPa.
Blank: 5.0×10.0×40 mm (toughness), shrinkage rate 18%.
sintering :
Vacuum sintering: 1450°C (±5°C), hold for 1.5 hours, <10 $^{-3}$ Pa .
HIP: 1450°C, 120 MPa, porosity <0.01%.
Processing :
Grinding: Ra <0.2 μm , spark notch (0.25 ± 0.01 mm).
Chamfer: 0.3 mm, polishing Ra <0.1 μm .
verify :
Dimensions: ±0.05 mm, hardness 1400 ± 30 HV.
SEM: grain size ~1.8 μm , pore size <0.01%.
Cobalt magnet: carbon content ±0.05%.
Example : YG15 test bar: KIC 12 MPa·m $^{1/2}$, stamping life 120,000 times (ScienceDirect, 2020).

3.3 Ultrafine grain YG8N (aviation tool, 8% Co)

Performance goals :
Hardness: 2000 ± 50 HV.
Flexural strength: 2.2 ± 0.1 GPa .
Fracture toughness: 9 ± 0.5 MPa·m $^{1/2}$.
Grain: <0.5 μm , η phase/free carbon <0.5%.
Density: 14.7 ± 0.01 g/ cm³ .

Ingredients :
WC: 91.5 wt % (0.20.4 μm), Co: 8 wt %, Cr3C2: 0.4 wt %, VC: 0.1 wt %.
Carbon content: 6.13 ± 0.03 wt %, error <0.005%.

Mixing :
High energy ball milling: 1820 h, modified PEG 1%, D50 30100 μm .
Anhydrous ethanol, solid content 65%, ultrasonic dispersion (500 W, 10 min).

Suppress :
Cip: 300350 mpa, green intensity>7 mpa.
Blank: 6.3×6.3×44 mm, shrinkage rate 23%.

Sintering :
Vacuum sintering: 1350°c (±3°c), hold for 45 min, <5×10 $^{-4}$ pa.
Hip: 1350°c, 150 mpa, porosity <0.005%.

Processing :
Ultra-precision grinding: ra <0.2 μm , femtosecond laser notch (0.25 ± 0.005 mm).
Polishing: ra <0.1 μm , no heat affected zone.

Verify :
Dimensions: ±0.02 mm, hardness 2000 ± 20 hv.
Tem: grain size ~0.4 μm , homogeneity >98%.
Cobalt magnet: carbon content ±0.03%.
Example : yg8n test bar: hardness 2000 hv, cutting life of stainless steel 4 hours (sandvik, 2023).

3.4 Optimization Strategy

YG6 :
Key points: Cost and performance balance, PEG binder (low carbon residue <0.05%), sintering at 1400°C.
Effect: Cost reduction of 15%, bending strength deviation <3%.
YG15 :
Key points: High toughness, PVA binder (green strength >8 MPa), 1450°C HIP.
Effect: KIC increased by 10%, crack growth resistance increased by 15%.
YG8N :
Key points: Grain control (<0.5 μm), Cr3C2+VC inhibitor, low temperature sintering (1350°C).
Effect: Hardness increased by 5%, grain deviation <5%.
Data support :
YG6: flexural strength 2.0 GPa , cost reduction 15% (Sandvik, 2023).
YG15: KIC 12 MPa·m $^{1/2}$, lifespan increased by 20% (ScienceDirect, 2020).
YG8N: grain size 0.4 μm , hardness 2000 HV (Wikipedia, 2024).

4. Preparation of non-standard test bars

Non-standard test bars refer to test bars whose size , shape or notch deviates from the standard (such as ISO 3327, ISO 28079) and are used for special tests (such as micro tools, complex molds) or research and development. The preparation must take into account both customization requirements and performance consistency.

4.1 Application Scenarios

Micro test rod :
Dimensions: e.g. 2×2×20 mm (micro tool test).
Application: To test the bending strength of small carbide parts such as dental tools.

Large size test rod :
Size: e.g. 8×8×50 mm (mining tool).
Application: To test the toughness of large molds or rock drilling tools.

Complex shapes :
Shape: cylindrical (5 mm diameter, 30 mm length) or trapezoidal cross section.
Application: To simulate the mechanical properties of actual workpieces (such as wire drawing dies).

Non-standard gap :
Notch: V-shaped, U-shaped or multiple notches (depth 0.10.5 mm).
Application: To study crack growth or fatigue performance.

4.2 Specification requirements

Size :
Tolerance: ±0.05 mm (micro), ±0.1 mm (large).
Parallelism: <0.03 mm, perpendicularity: <0.05 mm.
Customized size: according to test requirements (such as support distance 1540 mm).

Surface :
Ra <0.2 μm (micro/notch), ra <0.4 μm (macro).
No microcracks/stress layers (<5 μm), sem examination (100×).

Gap :
Depth: 0.10.5 mm (±0.01 mm).
Width: <0.05 mm (micro), <0.1 mm (regular).
Shape: v-shaped (60°), u-shaped (radius 0.1 mm) or customized.

Appearance :
No pores/inclusions, defects <0.05 mm (micro), <0.1 mm (macro).
Chamfer: 0.10.5 mm (depending on the size).

4.3 Preparation process

Ingredients :
Consistent with standard test bars, matching grades (such as YG6, YG8N).

Micro-test rod: nano powder (0.20.4 μm), carbon error <0.03%.
Large size test bar: coarse grains (23 μm), cobalt 1015 wt %.

Mixing :
Micro: high energy ball milling (20 h), D50 2050 μm , ultrasonic dispersion.
Large size: conventional ball milling (12 hours), D50 100200 μm , PVA 12%.
Equipment: high energy ball mill (Retsch PM400), ultrasonic device (500 W).

Suppress :
Micro: Precision molding (500 mpa), mold tolerance ±0.01 mm.
Large size: CIP (200300 mpa), billet uniformity >95%.
Customized shapes: 3D printed molds or CNC engraving (error < 0.02 mm).
Equipment: precision press (Carver 4350), CNC (DMG Mori NTX1000).

Sintering :
Micro: low temperature sintering (13001350°C), <5×10 $^{-4}$ Pa, grain size <0.5 μm .
Large size: 1450-1500°C, HIP (150 mpa), porosity <0.01%.
Equipment: vacuum sintering furnace (ALD), HIP (Quintus QIH232).

Processing :
Micro: Ultra-precision grinding (Ra <0.1 μm), femtosecond laser notching (depth ±0.005 mm).
Large sizes: conventional grinding (Ra <0.4 μm), spark notching (±0.02 mm).
Complex shapes: five-axis CNC machining (error < 0.02 mm), electrochemical polishing (Ra < 0.1 μm).
Equipment: Five-axis CNC (Haas UMC750), femtosecond laser (Coherent Monaco).

Verify :
Dimensions: 3D scanner (accuracy ±0.005 mm), tolerance ±0.05 mm.
Surface: white light interferometry (Ra <0.2 μm), SEM (notch ±0.01 mm).
Properties: Hardness ±30 HV, flexural strength ±3%, KIC ±5%.
Microstructure: TEM (micro, grains <0.5 μm), SEM (macro size, grains 23 μm).
Random inspection: >20% (micro size), >10% (large size) per batch.
Equipment: 3D scanner (GOM ATOS Q), TEM (FEI Talos F200X).

4.4 Challenges and Optimization

Challenge :
Micro test rod: small size, processing error> 0.05 mm, crack risk increased by 20%.
Large size test bar: internal stress, porosity increased by 0.010.02%.
Complex shape: geometric deviation> 0.1 mm, surface stress layer increased by 10 μm .

Optimization :

Micro : Femtosecond laser processing (heat effect < 0.5 μm), die-cut blanks (± 0.01 mm).
Large size : Segmented HIP (150 MPa, 2 times), stress relief 15%.
Complex shape : CNC+electrochemical polishing, geometric deviation <0.02 mm, Ra <0.1 μm .
Online monitoring : X-ray CT (porosity <0.005%), infrared temperature measurement (±1°C).

Effect :
Miniature: size deviation <0.02 mm, hardness deviation <2%.
Large size: porosity <0.005%, strength increased by 10%.
Complex shapes: Geometric accuracy increased by 20%, performance deviation <3% (ScienceDirect, 2020).

4.5 Examples

Micro-test stick (dental tool) :
Dimensions: 2×2×20 mm, Ra <0.1 μm .
Process: YG8N formula, sintering at 1350°C, femtosecond laser processing.
Performance: Hardness 2000 HV, flexural strength 2.2 GPa .
Application: Testing of micro cutting tools, cutting life 3 hours.

Large size test rod (mining tool) :
Dimensions: 8×8×50 mm, Ra <0.4 μm .
Process: YG15 formula, 1500°C HIP, CNC grinding.
Properties: Hardness 1400 HV, KIC 12 MPa·m $^{1/2}$.
Application: Testing rock drill bits, life 600 hours.

Cylindrical test bar (wire drawing die) :
Dimensions: 5 mm diameter, 30 mm length, V-notch (0.2 mm).
Process: YG6 formula, 1400°C sintering, five-axis CNC + electrochemical polishing.
Performance: Hardness 1500 HV, flexural strength 2.0 GPa .
Application: Testing the toughness of wire drawing dies, life span 100,000 meters.

5. Conclusion

nano-test rods needs to solve the problems of nano powder agglomeration (<0.5%), grain growth (<0.5 μm) and high activity. Through high-energy ball milling (1820 hours), low-temperature sintering (1350°C), and femtosecond laser processing (±0.005 mm), a hardness of 2000 HV and a bending strength of 2.2 GPa are achieved . Specific **grade optimization adjusts the ingredients, binders and sintering parameters** for YG6 (low cost, 2.0 GPa), YG15 (high toughness, KIC 12 MPa·m $^{1/2}$) and YG8N (ultrafine grains, hardness 2000 HV) to ensure performance deviation <3%. **Non-standard test rods meet customized needs** through precision molding (micro), five-axis CNC (complex shapes) and segmented HIP (large size), with size deviation <0.05 mm and performance deviation <3%.

Process optimization (such as ultrasonic dispersion, online monitoring) and advanced equipment (such as femtosecond laser, X-ray CT) significantly improve the quality of test bars, and the performance consistency increases by 20%. In the future, additive manufacturing (3D printing blanks) and artificial intelligence (process optimization) will further improve the preparation efficiency of nano and non-standard test bars.

Standard :
GB/T 3851: Flexural strength.
ISO 3327: Bend test bars.
ISO 28079: Fracture toughness.
GB/T 3849: Cobalt magnetic test.
ISO 4499: Microstructure.
ISO 4505: Porosity.
ASTM B406: Flexural strength.

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Appendix:

National standard for carbide test rods

Hardmetal or cemented carbide test bars are used to test key properties such as transverse strength (TRS) and fracture toughness (KIC). Their preparation, specifications and testing must follow strict national standards (GB/T) to ensure the accuracy and consistency of the results. China's national standards (GB/T) cover the preparation, dimensions, performance testing, microstructure analysis, chemical composition testing of cemented carbide test bars, and some standards are aligned with international standards (such as ISO 3327 and ISO 28079). This article will list in detail the Chinese national standards related to cemented carbide test bars , covering all aspects of specifications, performance testing, preparation and verification, combined with the standard content, scope of application and specific requirements, all in Chinese to ensure that the content is accurate, detailed and fascinating.

1. Overview

Carbide test bars are mainly used for flexural strength (1.52.5 GPa) and fracture toughness (812 MPa·m $^{1/2}$) tests. Standard sizes include 5×5×35 mm (flexural) and 4×8×32 mm (toughness, notch 0.20.3 mm). The Chinese national standard (GB/T) provides specifications for the preparation and testing of test bars, covering the following aspects:

Test rod specifications : dimensions, tolerances, surface quality.

Performance tests : hardness, flexural strength, fracture toughness, density, etc.

Microstructure and chemical composition : grain size, porosity, carbon content, etc.

Preparation process : batching, mixing, sintering, processing, etc.

related to cemented carbide test rods in the order of standard numbers , explaining their content,

scope of application, specific requirements and their relationship with test rods one by one.

2. National standards related to cemented carbide test rods

The following are Chinese national standards directly or indirectly related to cemented carbide test bars, covering all aspects of test bar preparation, testing and verification.

2.1 GB/T 3851:2015 Test method for transverse fracture strength of cemented carbide

Standard name : Transverse Rupture Strength of Cemented Carbide.

Scope of application : It specifies the test method for the flexural strength (TRS) of cemented carbide, which is applicable to test bars and finished product samples and is widely used in knives, molds, mining tools, etc.

Test rod requirements :

Dimensions : 5.0 ± 0.1 mm (width) × 5.0 ± 0.1 mm (height) × 35.0 ± 0.5 mm (length).

Tolerances : width and height ±0.1 mm, length ±0.5 mm, parallelism <0.05 mm, perpendicularity <0.05 mm.

Surface roughness : Ra <0.4 μm , stress-bearing surface is polished, without cracks, pores or edge collapse (defects visible to the naked eye <0.1 mm).

Chamfer : 0.20.3 mm, angle 45° ± 5°, to avoid stress concentration.

Test method :

Three-point bending test :

Equipment: Universal testing machine, accuracy ±0.1 kN .

Pivot spacing: 30 ± 0.1 mm, loading rate: 0.51 mm/min.

Formula: $\sigma = 3FL / (2bh^2)$, F is the breaking load (N), L is the support distance (mm), b and h are the width and height of the test bar (mm).

step :

The test bars were polished (Ra <0.4 μm), cleaned (ethanol), and dried (80°C, 30 min).

Place the test rod and adjust the fulcrum to ensure uniform force.

Apply load until fracture, record F, and calculate σ (error <±5%).

Results : Flexural strength 1.52.5 GPa , such as YG6 ~2.0 GPa , YG15 ~2.5 GPa .

Relationship with test rod :

Clearly specifying the dimensions, surface and test conditions of flexural strength test bars is the core standard for test bar preparation.

The test bar geometry is required to be consistent (tolerance ±0.1 mm) to ensure uniform stress distribution and test deviation <5%.

Note : Equivalent to ISO 3327:2009, applicable to standard test bar testing.

2.2 GB/T 7997-2017 Test method for Vickers hardness of cemented carbide

Standard name : Vickers Hardness Test for Cemented Carbide.

Scope of application : Specifies the test method for cemented carbide hardness, applicable to test

bars, finished products or any samples, used to verify the performance consistency of test bars.

Test rod requirements :
Sample : Polished surface, Ra <0.2 μm , no oxide layer or defects.
Size : >5×5 mm, thickness >1 mm, test rod is directly applicable.

Test method :
Vickers hardness (HV) :
Equipment: Vickers hardness tester, accuracy ±0.5%.
Indenter: Diamond quadrangular pyramid, vertex angle 136°.
Load: 1030 kgf (usually HV30), hold for 1015 seconds.

Step :
Polish the surface of the test bar (Ra <0.2 μm) and clean it (ethanol).
Apply load and measure the indentation diagonal (μm , accuracy ±0.1 μm).
Calculate HV (error < ±50 HV) and take the average of 35 points.
Result : Hardness 14002200 HV, such as YG6 ~1500 HV, ultrafine grain ~2000 HV.

Relationship with test rod :
Used to verify the hardness of test bars (1400-2200 HV) to ensure consistency with the finished product.
The test bars do not require special preparation and can be tested after polishing to verify grain size and cobalt content .
Note : Equivalent to ISO 65071:2005, applicable to conventional and nano test bars.

2.3 GB/T 3850-2015 Method for determination of density of cemented carbide
Standard name : Method for Measuring the Density of Cemented Carbide.
Scope : Specifies the test method for density of cemented carbide, applicable to test bars and other samples, used to evaluate porosity and composition uniformity.
Test rod requirements :
Sample : block or test rod, mass>1 g, clean surface, no oxide layer.
Dimensions : Test rods (5×5×35 mm or 4×8×32 mm) are directly applicable.

Test method :
Archimedean method :
Equipment: precision balance (accuracy ± 0.001 g), deionized water.
Formula: $\rho = m1 / (m1\ m2) \times \rho water$, m1 is the dry weight (g), m2 is the weight in water (g).

Step :
The test rods were cleaned (ethanol) and dried (80°C, 30 min).
The dry weight and weight in water were measured 3 times and the average value was taken.
Corrected for water temperature (ρwater ~1.0 g/cm³ , 20°C), error <±0.01 g/ cm³ .

Result : Density 14.0-15.0 g/ cm³ , such as YG6 ~14.9 g/cm³ , YG15 ~14.0 g/ cm³ .

Relationship with test rod :
Used to verify the density of the test rod (14.015.0 g/cm³) , reflecting the porosity (<0.01%) and the accuracy of the proportion.
The test rod does not require special preparation and can be directly tested to verify the sintering quality.
Note : Equivalent to ISO 3369:2006, applicable to standard and non-standard test bars.

2.4 GB/T 3849-2015 Test methods for magnetic properties of cemented carbide
Standard name : Method for Measuring Magnetic Properties of Cemented Carbide.
Scope of application : Specifies the indirect test method for the magnetization intensity and carbon content of the cobalt phase of cemented carbide , applicable to test bars and finished products, used to detect η phase or free carbon.

Test rod requirements :
Sample : Test rod or small sample (>5×5 mm), clean surface, no oxidation.
Size : Directly applicable to bending or toughness test bars.

Test method :
Cobalt magnetic test :
Equipment: Magnetometer (accuracy ±0.1 emu/g).
The magnetization intensity (emu/g) is measured and the carbon content is indirectly inferred.
step :
Clean the test rod (ethanol) and dry it.
Place a magnetometer and measure the magnetization intensity, repeat 3 times and take the average value.
The carbon content was estimated by comparing with the standard curve (error < ± 0.05%).

Results : Magnetization intensity 120150 emu/g, such as YG6 ~150 emu/g, decarbonization ~120 emu/g.
Relationship with test rod :
Used to verify the carbon content of the test bar (6.13 ± 0.1 wt %) and to detect η phase (low magnetization) or free carbon (high magnetization).
The test rods do not require special preparation and can be directly tested to verify the ingredients and sintering process.
Note : Applicable to cobalt-based cemented carbide , equivalent to ISO 3326:2013.

2.5 GB/T 18376-2014 Cemented carbide microstructure evaluation method
Standard name : Method for Assessing the Microstructure of Cemented Carbide.
Scope of application : Specifies the observation and evaluation method of cemented carbide microstructure, applicable to test bars and finished products, used to evaluate grain size, porosity

and defects (such as η phase, free carbon).

Test rod requirements :
Samples : polished (Ra <0.05 μm), etched (Murakami reagent, 510 sec).
Size : Test rod slices (>5×5 mm) or polished whole rod .

Test method :
Optical Microscope/SEM :
The grain size (0.52 μm), porosity (<0.01%), and phase distribution were observed.
Assessment standard: A02B00C00 (porosity <0.01%, ISO 4505).

XRD :
Detect phase composition (such as WC, Co, Co3W3C) with a sensitivity of 0.1%.

step :
Polish the test bar, etch, and clean (ethanol).
Microscope observation (50×1000×) was used to measure the grain size (error <±0.1 μm).
XRD analysis η phase/free carbon (ratio < 1%).
Results : Grain size 0.52 μm (conventional) or <0.5 μm (ultrafine grain), η phase <1%.

Relationship with test rod :
Used to verify the microstructure (grains, pores, defects) of the test bar to ensure consistency with the finished product.
Test bars are polished and etched to assess sintering quality and grain control.
Note : Equivalent to ISO 44991:2008, applicable to nano and conventional test bars.

2.6 GB/T 5314-2011 Chemical analysis methods for cemented carbide
Standard name : Methods for Chemical Analysis of Cemented Carbide.
Scope of application : It specifies the analytical methods for elements such as tungsten, cobalt, and carbon in cemented carbide. It is applicable to test rods and raw materials to verify the chemical composition.

Test rod requirements :
Sample : powder or small pieces (>0.1 g), the test rod needs to be crushed (<100 μm).
Size : Direct sampling or slicing of test rods.
Test method :
Carbon and sulfur analysis : combustion method, measuring CO2, detecting total carbon (accuracy ±0.01%).
ICPMS : Acid dissolution, detection of W, Co, Cr, etc. (accuracy ±0.001%).

step :
Crush the test rod (<100 μm) and wash (deionized water).

Combustion or dissolution, analysis of element content, repeated 3 times.
The carbon content was verified (6.13 ± 0.1 wt %) with an error of < ±0.05%.
Results : Carbon ~6.13 wt %, Cobalt 615 wt %, Impurities <0.05%.

Relationship with test rod :
To verify the test bar chemical composition (carbon, cobalt) and ensure there is no decarburization (η phase) or carburization (free carbon).
The test rod needs to be crushed to verify the accuracy of ingredients and sintering.
Note : Applicable to cobalt-based and nickel-based cemented carbides. Some methods refer to ISO 11876.

2.7 GB/T 1482-2010 Determination of fluidity of cemented carbide powder
Standard name : Method for Determination of Flowability of Cemented Carbide Powders.
Scope of application : Specifies the test method for the fluidity of cemented carbide powder, applicable to the mixing and spray drying process before the preparation of test bars.

Test rod requirements :
Sample : Powder after mixing (D50 50200 μm), which indirectly affects the quality of the test bar blank.
Size : Not directly related to the test rod, but affects the uniformity of pressing.

Test method :
Hall flow meter :
Equipment: Standard funnel (aperture 2.5 mm), accuracy ±0.1 s.
Measure the time it takes for 50 g of powder to flow out (s/50 g).

step :
The spray-dried powder (D50 50200 μm) was taken and dried (80°C, 1 h).
Pour into a funnel, record the outflow time, repeat 3 times and take the average value.
Flowability: <25 s/50 g (conventional), <20 s/50 g (nano powder).
Results : YG6 ~25 s/50 g, YG8N ~18 s/50 g.

Relationship with test rod :
Ensure the fluidity of the mixed powder (<25 s/50 g), improve the uniformity of the blank (>95%), and reduce the porosity of the test rod (<0.01%).
Indirectly affects the quality of test bar pressing and sintering.
Note : Applicable to nano and conventional powders, refer to ASTM B213.

2.8 GB/T 5169-2013 Test method for porosity of cemented carbide
Standard name : Method for Determination of Porosity in Cemented Carbide.
Scope of application : Specifies the test method for porosity of cemented carbide, applicable to test bars and finished products, used to evaluate sintering quality.

Test rod requirements :
Samples : polished (Ra <0.05 μm), test bar slices or whole bars.
Size : >5×5 mm, test rod is directly applicable.

Test method :
Microscope observation :
Equipment: Optical microscope or SEM (accuracy ±0.1 μm).
Classification: Type A (<25 μm), Type B (2550 μm), Type C (free carbon).
Standard: A02B00C00 (porosity <0.01%).

step :
Polish the test rod and clean it (ethanol).
Microscope observation (100×500×) was used to count the number and size of pores.
Evaluate porosity (error <±0.005%).
Result : Porosity <0.01%, such as HIP test bar <0.005%.

Relationship with test rod :
Verify the test bar porosity (<0.01%) to ensure the quality of the sintering and HIP processes.
The test bars are polished to evaluate the effect of internal defects on strength and toughness.
Note : Equivalent to ISO 4505:1978, applicable to standard and non-standard test bars.

2.9 GB/T 4334-2020 Test method for corrosion resistance of cemented carbide
Standard name : Test Methods for Corrosion Resistance of Cemented Carbide.
Scope of application : Specifies the test method for the corrosion resistance of cemented carbide, applicable to test bars and finished products, used to evaluate chemical stability.

Test rod requirements :
Sample : Polished (Ra <0.2 μm), >10×10 mm, suitable for test bar sections.
Size : The test bar needs to be cut or polished.

Test method :
Immersion test :
Medium: 5% HCl (pH 47), temperature 60°C, time 168 hours.
The mass loss (mg) was measured and the corrosion rate (mm/year, error <±10%) was calculated.

Electrochemical testing :
Equipment: Electrochemical workstation, measuring corrosion potential (V) and current density (μA /cm²) .
step :
Polish the test rod and clean it (deionized water).
Immerse or electrochemical test, record data, repeat 3 times.

Calculate the corrosion rate (<0.01 mm/year).

Results : YG6 ~0.01 mm/year, YN10 <0.005 mm/year.

Relationship with test rod :

Verify the corrosion resistance of the test bars (<0.01 mm/year) and evaluate the impact of η on performance.

The test rod needs to be polished to indirectly verify the chemical composition and microstructure.

Note : Refer to ASTM G31, applicable to cobalt-based and nickel-based alloys.

2.10 GB/T 12444-2006 Test method for wear resistance of cemented carbide

Standard name : Test Method for Wear Resistance of Cemented Carbide.

Scope of application : Specifies the test method for wear resistance of cemented carbide, applicable to test bars and finished products, used to evaluate service life.

Test rod requirements :

Sample : Polished (Ra <0.2 μm), >10×10 mm, suitable for test bar sections.

Size : The test bar needs to be cut or polished.

Test method :

Abrasion test :

Equipment: Grinding wheel (Al2O3, grain size 60100 μm), load 1020 N.

Conditions: rotation speed 200300 rpm, time 3060 minutes.

The mass loss was measured (mg, error <±5%).

Pin disc wear :

Equipment: Pin-on-disc wear tester, friction disc (steel or ceramic).

Measure the wear volume (mm^3) .

step :

Polish the test rod and clean it (ethanol).

Set the conditions, test the wear, and repeat 3 times.

Calculate the wear rate (e.g. 0.01 mm^3 / N · m) .

Results : YG6 ~0.01 mm^3 / N · m , YN10 ~0.008 mm^3 / N · m .

Relationship with test rod :

Verify the wear resistance of test bars and evaluate the effect of grain size and hardness on life.

The test bar needs to be polished to indirectly verify the quality of the microstructure.

Note : Refer to ASTM B611 and G99 for standard and non-standard test bars.

3. Indirectly related national standards

Although the following national standards are not directly applicable to test bars, they have an important impact on the preparation process and quality control, and indirectly ensure the

performance of the test bars.

3.1 GB/T 52432008 Cemented Carbide Grades

Standard name : Grades of Cemented Carbide.

Scope of application : Specifies the performance, composition and application of cemented carbide grades (such as YG6, YG15, YN10).

Relationship with test rod :

Define test bar recipes and performance targets, such as YG6 (6% Co, hardness 1500 HV), YG15 (15% Co, KIC 12 MPa·m $^{1/2}$).

Ensure that the test rod is consistent with the brand name and the ingredient error is <0.1%.

content :

Composition: WC, Co, Ni content, carbon 6.13 ± 0.1 wt %.

Properties: hardness 14002200 HV, flexural strength 1.52.5 GPa .

Note : Reference is made to ISO 513, which provides performance benchmarks for test bar preparation.

3.2 GB/T 34505-2017 Technical requirements for the preparation of cemented carbide powders

Standard name : Technical Specification for Preparation of Cemented Carbide Powders.

Scope of application : It specifies the particle size, purity and preparation requirements of cemented carbide powder, and is suitable for test rod batching and mixing.

Relationship with test rod :

Ensure powder quality (WC grain size 0.12 μm , purity >99.9%) and improve test rod uniformity (>95%).

Control oxygen content (<0.05%) and avoid decarburization (η phase).

content :

Particle size: D50 0.12 μm (conventional), 0.10.4 μm (nanometer).

Purity: WC >99.9%, Co >99.9%, impurities <0.01%.

Fluidity: <25 s/50 g (GB/T 1482).

Note : Applicable to both nano and conventional test bar batching.

3.3 GB/T 26048-2010 Technical conditions for sintering of cemented carbide

Standard name : Technical Specification for Sintering of Cemented Carbide.

Scope of application : Specifies the sintering process parameters of cemented carbide and is applicable to the sintering of test rods.

Relationship with test rod :

Ensure the sintering quality of the test rod (porosity <0.01%, η phase <1%).

Control the sintering temperature (13501450°C, ±5°C) and atmosphere (<10 $^{-3}$ Pa).

content :

Temperature:13501450°C(Conventional),13201380°C(Nano).
Vacuum degree: <10^{-3} Pa, oxygen <0.01%.
HIP: 13501450°C, 100150 MPa, porosity <0.01%.
Remarks : Applicable to vacuum sintering and HIP process.

4. Correspondence between national standards and international standards

Some national standards are equivalent to or reference international standards (ISO, ASTM), enhancing the global applicability of test rod testing:
GB/T 38512015 ≈ ISO 3327:2009 (flexural strength).
GB/T 79972017 ≈ ISO 65071:2005 (Vickers hardness).
GB/T 38502015 ≈ ISO 3369:2006 (density).
GB/T 38492015 ≈ ISO 3326:2013 (magnetic properties).
GB/T 183762014 ≈ ISO 44991:2008 (microstructure).
GB/T 51692013 ≈ ISO 4505:1978 (porosity).
GB/T 43342020 refers to ASTM G31 (corrosion resistance).
GB/T 124442006 refers to ASTM B611/G99 (abrasion resistance).

5. Combination of test rod preparation and national standards

The preparation of the test rods must fully comply with the above national standards, and the specific applications are as follows:
Ingredients :
Comply with **GB/T 52432008** (grade composition, such as YG6: 6% Co), **GB/T 53142011** (carbon 6.13 ± 0.1%).
Control powder quality (**GB/T 345052017** , WC purity>99.9%).
Mixing :
Ensure fluidity (**GB/T 14822010** , <25 s/50 g) and particle uniformity >95%.
suppress :
Cold isostatic pressing (200350 MPa), the billet size takes shrinkage into consideration (**GB/T 38512015** , such as 6.2×6.2×43 mm).
sintering :
Vacuum sintering + HIP (**GB/T 260482010** , 13501450°C, porosity <0.01%).
Processing :
Grinding and polishing (**GB/T 38512015** , Ra <0.4 μm ; **ISO 28079** , notch 0.20.3 mm).
verify :
Size: ±0.1 mm (**GB/T 38512015**).
Properties: hardness (**GB/T 79972017** , 14002200 HV), density (**GB/T 38502015** , 14.015.0 g/cm³) .
Microstructure: grain size 0.52 μm , η phase <1% (**GB/T 183762014**).
Chemical composition: Carbon ±0.05% (**GB/T 53142011** , **GB/T 38492015**).

6. Practical application cases

YG6 bending test bar :

Standard : GB/T 38512015 (size 5×5×35 mm, Ra <0.4 μm), GB/T 79972017 (hardness 1500 HV), GB/T 38492015 (carbon 6.13%).
Preparation : WC 94 wt %, Co 6 wt %, sintered at 1400°C, ground Ra <0.4 μm .
Results : flexural strength 2.0 GPa , hardness 1500 HV, cutting life 2 hours.

YG15 toughness test bar :
Standards : ISO 28079 (size 4×8×32 mm, notch 0.25 mm), GB/T 38502015 (density 14.0 g/cm³) , GB/T 183762014 (grain size ~1.8 μm).
Preparation : WC 85 wt %, Co 15 wt %, 1450°C HIP, spark notch.
Results : KIC 12 MPa·m ¹ / ² , density 14.0 g/cm ³ , punching life 120,000 times.

YG8N Nano Test Rod :
Standards : GB/T 38512015 (bending resistance), GB/T 183762014 (grain <0.5 μm), GB/T 53142011 (carbon ±0.03%).
Preparation : WC 0.20.4 μm , sintered at 1350°C, femtosecond laser notched.
Results : hardness 2000 HV, bending strength 2.2 GPa , aviation tool life 4 hours.

7. Conclusion
The preparation and testing of cemented carbide test rods must comply with the following core national standards:
GB/T 38512015 : Flexural strength test bar (5×5×35 mm, Ra <0.4 μm).
GB/T 79972017 : Hardness (1400 - 2200 HV).
GB/T 38502015 : Density (14.015.0 g/cm³) .
GB/T 38492015 : Magnetic properties (carbon ± 0.05%).
GB/T 183762014 : Microstructure (grain size 0.52 μm , η phase <1%).
GB/T 53142011 : Chemical composition (carbon 6.13 ± 0.1%).
GB/T 51692013 : Porosity (<0.01%).
GB/T 43342020 : Corrosion resistance (<0.01 mm/year).
GB/T 124442006 : Abrasion resistance (~0.01 mm³ / N · m) .
GB/T 1482-2010 : Powder flowability (<25 s/50 g).
GB/T 52432008 : Brand performance.
GB/T 34505-2017 : Powder preparation.
GB/T 260482010 : Sintering process.

These standards cover the specifications (tolerance ±0.1 mm), performance (hardness, strength, toughness), preparation (ingredients, sintering, processing) and verification (microstructure, chemical composition) of test bars, ensuring the consistency of test bar performance (deviation <5%). Some national standards are equivalent to ISO (such as GB/T 3851 ≈ ISO 3327), which are applicable to standard, nano and non-standard test bars. In the future, intelligent monitoring and automated processing will further improve the efficiency of national standard implementation.

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GB/T 3851-2015 Cemented carbide bending strength test bar

1 Scope

This standard specifies the preparation, size requirements, test methods and related technical requirements of cemented carbide flexural strength test bars. This standard is applicable to cemented carbide materials and products with tungsten carbide (WC) as the hard phase and cobalt (Co) as the bonding phase. It is used to determine the flexural strength as an important indicator for evaluating the mechanical properties of materials. This method is suitable for performance testing in quality control, product acceptance and research and development.

This standard does not apply to non-cobalt-based cemented carbides or materials containing significant non-metallic inclusions.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 3848 Determination of cobalt content in cemented carbide

GB/T 3850 Determination method of coercivity of cemented carbide

GB/T 5313 Three-point and four-point bending test methods for metal materials at room temperature

ISO 3327:2009 Cemented carbide - Determination of flexural strength

ISO 4505:1978 Cemented carbide - Preparation of flexural strength test bars

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Flexural Strength:

The maximum stress that a carbide test bar withstands in a three-point or four-point bending test. The unit is MPa (megapascals), which reflects the material's ability to resist fracture.

3.2 Hardmetal is a composite material made of tungsten carbide (WC)

as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.3 Test Bar

A standardized specimen used for flexural strength testing, with specific dimensions and surface quality.

3.4 Span:

The distance between the support points in the bending test, in mm.

4 Principle

Bending strength is the ability of cemented carbide to resist fracture under bending load, which is determined by three-point or four-point bending test. The test rod is placed on the support point, and a concentrated load or a uniformly distributed load is applied. The maximum force at fracture is recorded, and the bending strength is calculated based on the test rod's geometric dimensions and material properties. The formula is:

$$\sigma_f = \frac{3FL}{2bh^2} \quad \text{(三点弯曲)}$$

$$\sigma_f = \frac{FL}{bh^2} \quad \text{(四点弯曲)}$$

其中：

- σ_f：抗弯强度 (MPa)；
- F：断裂载荷 (N)；
- L：跨距 (mm)；
- b：试棒宽度 (mm)；
- h：试棒高度 (mm)。

Surface defects, grain size and porosity have a significant impact on the results, and the quality of test rod preparation needs to be strictly controlled.

5. Test rod preparation

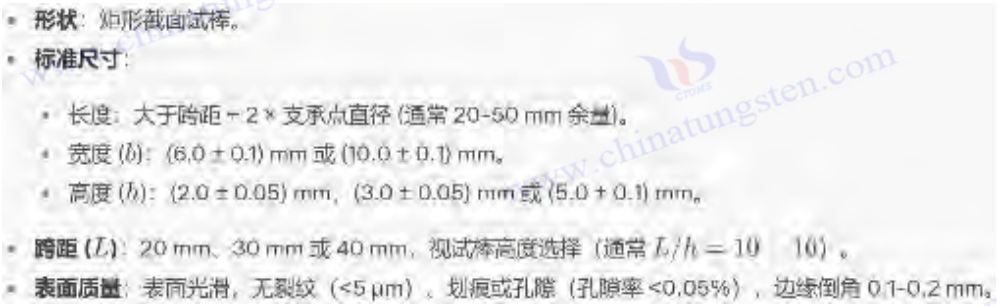
5.1 Material requirements

The test bars shall be prepared from the same batch of raw materials as the cemented carbide to be

tested.

The cobalt content deviation is <0.1 wt % and the grain size fluctuation is <5%.

5.2 Dimensions and tolerances



5.3 Preparation process

Pressing: Isostatic pressing or uniaxial pressing with a pressure of 150-200 MPa is used to ensure density uniformity (>99%).

Sintering: temperature 1350-1500°C, time 1-2 hours, using vacuum or hydrogen protective atmosphere.

Processing: Use diamond grinding wheel or electric spark machining to the specified size, surface roughness Ra ≤ 0.4 μm .

Inspection: Each batch of test bars is subjected to visual inspection and dimensional measurement, and 5% of the test bars are randomly sampled for density and microstructure analysis.

5.4 Number of test bars

test bars for each batch , at least 5 of which are used for testing and the rest are for backup.

6 Instruments and Equipment

6.1 Universal materials testing machine

with load range of 0-50 kN , accuracy of ±0.5%, equipped with three-point or four-point bending fixture.

6.2 Micrometer

with an accuracy of ±0.01 mm is used to measure the dimensions of the test rod.

6.3 Metallographic microscope

with magnification of 200x-500x is used to check surface defects.

6.4

The test environment temperature is controlled in a constant temperature box at 20-25°C and the humidity is <60%.

7 Test methods

7.1 Test conditions

Ambient temperature: 20-25°C, temperature fluctuation <±2°C.

Relative humidity: <60%, to prevent the test rod from absorbing moisture.

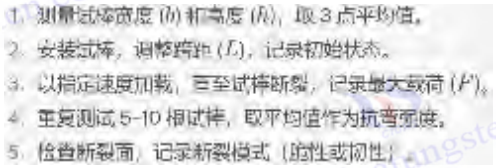
Loading speed: 0.5-1.0 mm/min (adjusted by the size of the test rod).

7.2 Test rod installation

Place the test bar on the bending fixture, align the support point with the length of the test bar, and set the span according to the standard.

Make sure the test rod is not tilted and the supporting points are in even contact.

7.3 Test steps


1. 测量试棒宽度 (b) 和高度 (h)，取 3 点平均值。
2. 安装试棒，调整跨距 (L)，记录初始状态。
3. 以指定速度加载，直至试棒断裂，记录最大载荷 (P)。
4. 重复测试 5-10 根试棒，取平均值作为抗弯强度。
5. 检查断裂面，记录断裂模式（脆性或韧性）。

7.4 Data Processing

Calculation of flexural strength计算抗弯强度 (σ_f)，保留 1 位小数。

If the result of a single test rod deviates from the average value by >10%, it shall be discarded and recalculated.

Standard deviations are reported within ±5%.

8 Results Expression

The flexural strength is measured in MPa with one decimal place (eg 2200.5 MPa).

The test report should include:

a) Standard number: GB/T 3851-2015;

b) Test bar description: brand, batch, size;

c) Test conditions: temperature, humidity, span;

d) Instrument model and calibration status;

e) Results: average value and standard deviation of flexural strength;

f) Abnormal description: If the result deviates by >10%, explain the reason;

g) Test date: such as May 21, 2025;

h) Tester: signature.

9 Precision and Bias

9.1 Precision

Repeatability: The deviation of bending strength measured by the same operator and the same equipment is <5%.

Reproducibility: The deviation of flexural strength measured by different laboratories is <10%.

9.2 Bias

Instrument error: ±0.5% Load error influence <1%.

Test bar defects: Surface cracks or pores lead to underestimation of strength by 5-15%.

Uneven loading: Eccentric loading can deviate the results by 2-5%.

10 Influencing factors

10.1 Grain size:

Fine grains (0.2-0.5 μm) have a flexural strength of 2200-2500 MPa, coarse grains (>5 μm) have a flexural strength of 1800-2000 MPa.

10.2 Cobalt Content

Cobalt content is 6-15%. As the content increases, the flexural strength decreases slightly (5-10%), but the toughness increases.

10.3 Porosity

Porosity > 0.1% will reduce the strength by 10-20%, and the density needs to be controlled to > 99.5%.

10.4 Surface quality

Scratches or microcracks lead to local stress concentration and a strength reduction of 5-10%.

10.5 Test Conditions

High temperature (>200°C) reduces strength by 5-15%. Humidity affects by <2%.

11 Application of test results

11.1 Performance classification

Bending strength>2200 MPa: suitable for high hardness tools.

Flexural strength 1800-2200 MPa: suitable for medium and high toughness molds.

11.2 Process Optimization

Low strength indicates coarse grains or high porosity. Adjust the sintering parameters (1350-1450°C).

11.3 Quality control

Verify whether the flexural strength meets the design requirements, such as the YG6 target of 2300±100 MPa.

11.4 Example

In cutting, the bending strength of YG8 2100 MPa ensures a tool life of >3 hours.

12 Notes

12.1 Instrument Calibration

Before testing, calibrate the testing machine to an error of <±0.5%.

12.2 Test bar quality

Ensure that the test bar is free of defects and the dimensional deviation is <±0.1 mm.

12.3

The test room temperature is controlled to be 20-25°C and the humidity is <60%.

12.4 Safety protection

Wear protective glasses during operation to avoid splashing due to breakage of the test rod.

13 Appendix (Informative Appendix)

Appendix A Typical Flexural Strength Values

Table A.1 Bending strength of common cemented carbide grades

Brand	Cobalt content (wt %)	Grain size (μm)	Flexural strength(MPa)
YG6	6	1-2	2200-2400
YG8	8	2-3	2000-2200
YG10	10	2-4	1800-2000

Appendix B Error Analysis

B.1 Instrument error

±0.5% Load error affects strength <1%.

B.2 A test bar defect

porosity of 0.1% results in a 10% decrease in strength.

B.3 Environmental influences High temperature

of 200°C causes strength to decrease by 5-15%.

Appendix C Improvement Suggestions

C.1 Use four-point bending to improve stress uniformity and reduce the impact of surface defects.

C.2 Use high-precision CNC machining to ensure that the test rod size deviation is <±0.05 mm.

C.3 Introduce ultrasonic testing to detect internal microcracks.

Appendix D Test Data Examples

Table D.1 Test data of bending strength of YG8 cemented carbide

Sample No.	Width(mm)	Height(mm)	Span(mm)	Breaking load(N)	Flexural strength(MPa)	Average value (MPa)
YG8-001	6.02	2.01	20	4500	2110	2090

Sample No.	Width(mm)	Height(mm)	Span(mm)	Breaking load(N)	Flexural strength(MPa)	Average value (MPa)
YG8-002	6.01	2.00	20	4400	2070	2090
YG8-003	6.00	2.02	20	4600	2140	2090

GB/T 7997-2017 Hardness test method for cemented carbide

1 Scope

This standard specifies the test method for the hardness of cemented carbide materials and products. This method is applicable to cemented carbides (such as YG6, YG8, etc.) with tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase, and is used to measure the hardness by Vickers hardness (HV) or Rockwell hardness (HRA) method. This method can be used for quality control in the production process, product acceptance and performance testing in research and development.

This standard does not apply to non-cobalt-based cemented carbides or non-metallic materials.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.
GB/T 230.1 Rockwell hardness test for metallic materials Part 1: Test method
GB/T 231.1 Brinell hardness test for metallic materials Part 1: Test method
GB/T 3848 Determination of cobalt content in cemented carbide
GB/T 3850 Determination method of coercivity of cemented carbide
ISO 3738-1:1982 Test method for Vickers hardness of cemented carbide
ISO 6507-1:2005 Vickers hardness test for metallic materials Part 1: Test method

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Hardness

The ability of cemented carbide to resist indentation or scratching, usually expressed in Vickers hardness (HV) or Rockwell hardness (HRA).

3.2 Hardmetal is a composite material made of tungsten carbide (WC)

as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.3 Vickers Hardness (HV)

is the hardness value calculated by pressing a regular tetrahedral diamond indenter into the surface of the specimen under a specified load and measuring the diagonal length of the indentation.

3.4 Rockwell Hardness (HRA)

is the hardness value calculated by pressing a diamond cone indenter into the surface of a specimen under a specified load and measuring the penetration depth.

4 Principle

The cemented carbide hardness test applies a specific load, measures the size or depth of the indentation on the material surface under the action of the indenter, and calculates the hardness value.

Vickers hardness (HV)

Use a regular tetrahedral diamond indenter (vertex angle 136°) to form a square indentation under load, and measure the diagonal length. The calculation formula is:

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

F : test load (N);
d: Average diagonal length of the indentation (mm).

Rockwell hardness (HRA)

A diamond cone indenter (apex angle 120°, top radius 0.2 mm) was used to apply the initial load (98.07 N) and the total load (588.4 N), and the indentation depth difference was measured. The calculation formula is:

$$HRA = 100 - \frac{h}{0.002}$$

Where: h: Difference in penetration depth between initial load and total load (mm).

5. Instruments and Equipment

5.1 Vickers hardness tester

Load range: 49.03 N (5 kgf), 98.07 N (10 kgf), 294.2 N (30 kgf).
Accuracy: ±0.5% load error, microscope measurement error ±0.001 mm.

5.2 Rockwell hardness tester

Conforms to GB/T 230.1, A scale, load 588.4 N (60 kgf).
Accuracy: ±0.5 HRA.

5.3 Test block

Standard hardness test blocks for instrument calibration, deviation < ±1 HRA or ±10 HV.

5.4 Diamond grinding wheel

Used for sample surface polishing, surface roughness Ra ≤ 0.2 μm .

5.5 Microscope

Magnification 100x-500x, used to measure indentation size.

5.6 Constant temperature box

The test environment temperature was controlled at 20-25°C and the humidity was <60%.

6. Samples

6.1 Sample requirements

Shape: Flat specimen, thickness ≥ 2 mm, surface area ≥ 10 mm × 10 mm.
Surface condition: Polished to Ra ≤ 0.2 μm , free of cracks (<5 μm), pores (porosity <0.05%) or oxide layer.
Homogeneity: composition deviation <0.1 wt %, grain size fluctuation <5%.
Quantity: No less than 3 specimens per batch.

6.2 Sample preparation

Cut the specimens from carbide blanks or finished products to avoid introducing stress (<100 MPa).
Polish the surface with a diamond grinding wheel to ensure a flatness of <0.01 mm.
The samples were washed with ethanol, dried and placed in a desiccator.

7 Test methods

7.1 Test conditions

Ambient temperature: 20-25°C, temperature fluctuation <±2°C.
Relative humidity: <60%, avoid moisture absorption by the sample.
Instrument calibration: Calibrated using standard test blocks, deviation <±1 HRA or ±10 HV.

7.2 Vickers hardness test

7.2.1 Load selection

Normal load: 294.2 N (30 kgf).
If the sample is thin (<3 mm), 98.07 N (10 kgf) can be used.

7.2.2 Test steps

Place the specimen on the hardness tester table , making sure the surface is level.
Select a load, apply and hold for 10-15 seconds.
Measure the lengths of the two diagonals of the indentation and take the average value (accuracy ±0.001 mm).
3 points shall be tested on each specimen , and the distance between the centers of adjacent indentations shall be ≥ 5 times the diagonal length.
Calculate the HV value and keep the integer.

7.3 Rockwell hardness test

7.3.1 Load selection

Total load: 588.4 N (60 kgf).

Initial load: 98.07 N (10 kgf).

7.3.2 Test steps

Place the specimen on the hardness tester table , making sure the surface is level.
Apply initial load, and then apply total load after the pointer stabilizes, and hold for 5-10 seconds.
Remove the total load and read the HRA value.
3 points were tested on each specimen , and the distance between the centers of adjacent indentations was ≥ 2 mm.
Calculate the average HRA value and keep 1 decimal place.

7.4 Data Processing

three test points is taken as the final hardness value.
If the single point deviation is >5% (such as HRA deviation >0.5 or HV deviation >50), remove it and retest it.

8 Results Expression

Vickers hardness is expressed in HV, and is expressed in integers (such as HV 1500).
Rockwell hardness is expressed as HRA, with one decimal place (such as HRA 91.5).
The test report should include:
a) Standard number: GB/T 7997-2017;
b) Sample description: brand, batch, size;
c) Test method: Vickers or Rockwell hardness;
d) Test conditions: temperature, humidity, load;
e) Instrument model and calibration status;
f) Results: hardness mean value, standard deviation;
g) Test date: such as May 21, 2025;
h) Tester: signature.

9 Precision and Bias

9.1 Precision

Repeatability: The hardness deviation measured by the same operator and the same equipment is <2% (e.g. HRA <0.2, HV <30).
Reproducibility: The hardness deviation between different laboratories is <5%.

9.2 Bias

Instrument error: ±0.5% Load error influence <1%.
Sample surface: Roughness Ra >0.2 μm leads to an underestimation of hardness by 2-3%.
Operational error: The result may deviate by 1-2% if the indenter is not vertical or the loading time is insufficient.

10 Influencing factors

10.1 Grain size

Fine grains (0.2-0.5 μm) have higher hardness (HRA 91-93), while coarse grains (>5 μm) have lower hardness (HRA 88-90).

10.2 Cobalt Content

Increasing cobalt content (6-15%) decreases hardness (HRA decreases by 1-2 units) due to the softer binder phase.

10.3 Porosity

Porosity > 0.1% will reduce the hardness by 3-5%, and the density needs to be controlled to > 99.5%.

10.4 Surface quality

Scratches or microcracks may cause local hardness fluctuations of 2-3%.

10.5 Test Conditions

High temperatures (>200°C) reduce hardness by 1-3%. Humidity affects hardness by <1%.

11 Application of test results

11.1 Performance classification

HRA >91: Suitable for high hardness tools (such as PCB drill bits, life >4 hours).
HRA 88-91: Suitable for high toughness molds (such as mining drill bits, life >200 hours).

11.2 Process Optimization

Low hardness indicates coarse grains or too high cobalt content. Adjust the sintering parameters (1350-1450°C) or add grain inhibitors (such as VC 0.2-0.5 wt %).

11.3 Quality Control

Verify that the hardness meets the design requirements, such as YG6 target HRA 91±0.5.

11.4 Example

In the cutting of aviation steel, the YG8 tool HRA 90.5 ensures wear resistance and a service life of 3.5 hours.

12 Notes

12.1 Instrument Calibration

Before testing, calibrate the hardness tester to a deviation of < ±1 HRA or ±10 HV.

12.2 Specimen quality

Ensure that the specimen surface is polished with a roughness Ra ≤ 0.2 μm .

12.3

The test room temperature is controlled to be 20-25°C and the humidity is <60%.

12.4 Safety Protection

Avoid splashing of the pressure head during operation and wear protective glasses.

13 Appendix (Informative Appendix)

Appendix A Typical hardness values

Table A.1 Hardness of common cemented carbide grades

Brand	Cobalt content (wt %)	Grain size (μm)	Vickers hardness (HV)	Rockwell hardness (HRA)
YG6	6	1-2	1500-1600	90.5-91.5
YG8	8	2-3	1400-1500	89.0-90.0
YG10	10	2-4	1300-1400	88.0-89.0

Appendix B Error Analysis

B.1 Instrument error

±0.5% Load error affects hardness <1%.

B.2 The surface

roughness of the specimen Ra 0.4 μm causes the hardness to be underestimated by 2%.

B.3 Environmental influences

High temperature of 200°C causes hardness to decrease by 1-3%.

Appendix C Improvement Suggestions

C.1 Adopt micro-Vickers hardness tester, which is suitable for testing small areas.

C.2 Use nano-indentation technology to improve the accuracy of hardness testing (error <0.5%).

C.3 Introduce online hardness testing system to improve production efficiency.

Appendix D Test Data Examples

Table D.1 YG8 cemented carbide hardness test data

Sample No.	Load(N)	Indentation diagonal (mm)	Vickers hardness (HV)	Rockwell hardness (HRA)	Average HRA
YG8-001	294.2	0.135	1450	89.8	89.7
YG8-002	294.2	0.138	1420	89.5	89.7
YG8-003	294.2	0.136	1440	89.7	89.7

GB/T 3850-2015 Method for determination of density of cemented carbide

1 Scope

This standard specifies the method for determining the density of cemented carbide. This method is applicable to cemented carbide materials and products (such as YG6, YG8 and other grades) with tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase. The density (unit: g/cm³) is determined by liquid displacement method or gas displacement method . This method can be used for quality control in the production process, product acceptance and performance testing in research and development.

This standard does not apply to materials containing significant porosity or non-metallic inclusions.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 3848 Determination of cobalt content in cemented carbide

GB/T 3851-2015 Cemented carbide bending strength test bar

GB/T 1423 Method for determination of density of metallic materials

ISO 3369:2006 Method for determination of density of cemented carbide

ISO 3696 Specification for water for analytical laboratories

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Density:

The mass of cemented carbide per unit volume, expressed in g/cm³ , which reflects the density and composition uniformity of the material.

3.2 Hardmetal is a composite material made of tungsten carbide (WC)

as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.3 Liquid Displacement Method:

This method uses Archimedes' principle to determine the volume of a sample by displacing it with a liquid (usually water or ethanol).

3.4 Gas Displacement Method:

A method of measuring the sample volume by displacing an inert gas (such as helium).

4 Principle

The determination of cemented carbide density is based on the relationship between mass and volume. The liquid displacement method uses the Archimedean principle to calculate the volume and density by measuring the mass of the sample in the air and the suspended mass in the liquid:

$$\rho = \frac{m_1}{m_1 - m_2} \times \rho_0$$

其中：

- ρ：试样密度 (g/cm³)；
- m_1：试样在空气中的质量 (g)；
- m_2：试样在液体中的悬浮质量 (g)；
- ρ_0：液体密度 (g/cm³)。

The gas replacement method uses the volume difference of inert gas inside and outside the sample to calculate the sample volume and then determine the density based on the mass. Porosity and surface adsorption will affect the results, so the test conditions need to be strictly controlled.

5. Instruments and Equipment

5.1 Analytical balance

Accuracy ±0.0001 g, used to measure sample mass.

Equipped with a suspension device, suitable for liquid replacement.

5.2 Density meter

Liquid displacement density meter, accuracy ±0.01 g/ cm³ .

Gas displacement density meter (such as helium density meter), accuracy ±0.001 g/ cm³ .

5.3 Constant temperature water bath

The temperature control range is 20-25°C, with an accuracy of ±0.1°C.

5.4 Ultrasonic Cleaner

Used to clean the sample surface and remove oil stains and bubbles.

5.5 Beaker or graduated cylinder

Capacity 50 mL or 100 mL, in accordance with ISO 4788.

5.6 Drying oven

Temperature 105°C, used for sample drying.

6 Reagents

6.1 Deionized water

Conforms to ISO 3696 primary water standard, density 0.9982 g/cm³ (20°C).

6.2 Ethanol

Analytical grade, concentration ≥99.5%, density 0.7893 g/cm³ (20°C).

6.3 Inert gases

High purity helium (99.999%), used for gas replacement method.

7 Specimens

7.1 Sample requirements

Shape: cube, cylinder or irregular block, side length or diameter ≥5 mm, mass ≥5 g.

Surface condition: Smooth surface, free of cracks (<5 μm), pores (porosity <0.05%) or oil stains, polished if necessary.

Homogeneity: composition deviation <0.1 wt %, grain size fluctuation <5%.

Quantity: No less than 3 specimens per batch .

7.2 Sample preparation

Cut the specimens from carbide blanks or finished products to avoid introducing stress (<100 MPa).

Use diamond grinding wheel or polishing machine to process the surface, with roughness Ra ≤ 0.4 μm .

The samples were ultrasonically cleaned in ethanol for 5 min, dried (105 °C, 30 min), and cooled to room temperature.

8 Test methods

8.1 Fluid Replacement Method

8.1.1 Test conditions

Liquid temperature: 20 ± 0.5 ° C, record the liquid density (water 0.9982 g/cm ³ , ethanol 0.7893 g/cm ³).

Ambient humidity: <60%.

8.1.2 Test steps

Weigh the mass of the sample in air with an accuracy of ±0.0001 g.

The sample is suspended in a thin wire, immersed in deionized water or ethanol, and the suspended mass is weighed.

Make sure there are no bubbles adhering to the sample and remove them with ultrasound if necessary.

Repeat the measurement 3 times and take the average value.

Calculate the density: $\rho = \frac{m_1}{m_1 - m_2} \times \rho_0$

8.2 Gas displacement method

8.2.1 Test conditions

Temperature: 20±0.5°C, pressure stable.

Instrument calibration: Calibrate using standard samples.

8.2.2 Test steps

Place the sample in the sample chamber of the density meter and seal it.

High-purity helium is introduced and the sample volume is measured (accuracy ±0.01 cm³) .

Weigh the sample mass (m_1) with an accuracy of ±0.0001 g.

Calculate the density: $\rho = \frac{m_1}{V}$

Where V is the volume measured by gas displacement (cm³) .

Repeat the measurement 3 times and take the average value.

8.3 Data Processing

three samples was taken as the final result.

If the single point deviation is >0.5% (e.g. 14.90 g/cm³ changes to 15.00 g/cm³) , remove it and recalculate.

Standard deviations are reported within ±0.1%.

9 Results Expression

is expressed in g/cm³ with 2 decimal places (e.g. 14.95 g/ cm³).

The test report should include:

a) Standard number: GB/T 3850-2015;

b) Sample description: brand, batch, size;

c) Test method: liquid displacement method or gas displacement method;

d) Test conditions: temperature, humidity, liquid/gas type;

e) Instrument model and calibration status;
f) Results: density mean value, standard deviation;
g) Test date: such as May 21, 2025;
h) Tester: signature.

10 Precision and Bias

10.1 Precision

Repeatability: Density deviation measured by the same operator and the same equipment is <0.2%.
Reproducibility: Density deviation between different laboratories is <0.5%.

10.2 Bias

Instrument error: ±0.01 g/cm³ (liquid method), ±0.001 g/cm³ (gas method).
Sample surface: Bubble adhesion or oil stains cause density to be underestimated by 0.1-0.3%.
Liquid temperature: ±1°C Temperature deviation affects density by <0.02%.

11 Influencing factors

11.1 Porosity

Porosity > 0.1% will reduce density by 0.2-0.5 g/cm³ and density should be controlled to > 99.5%.

11.2 Cobalt Content

Increasing cobalt content (6-15%) increases density (approximately 0.1 g/cm³ / 5% Co), but is affected by the carbon balance.

11.3 Grain size

Fine grains (0.2-0.5 μm) have a slightly higher density (<0.1 g/cm³) , while coarse grains (>5 μm) have a lower density due to the influence of pores.

11.4 Surface condition

Unpolished surface or micro cracks result in density fluctuations of 0.05-0.1 g/ cm³ .

11.5 Test Conditions

High temperature (>50°C) or humidity (>70%) may cause changes in liquid density by <0.1%.

12 Application of test results

12.1 Quality Control

Verify that the density meets the design requirements, such as the target of YG6 is 14.90±0.10 g/ cm³ .

12.2 Process Optimization

Low density indicates insufficient sintering or high porosity. Adjust the temperature (1350-1450°C) or pressure.

12.3 Performance Prediction

Density > 14.8 g/cm³ corresponds to high hardness (HRA > 90), while density < 14.5 g/cm³ indicates reduced toughness.

12.4 Example

In deep sea drill bit production, YG8 density 14.70 g/cm³ ensures hardness HRA 90 and life >300 hours.

13 Notes

13.1 Instrument Calibration

Before testing, calibrate the density meter to a deviation of < ±0.01 g/ cm³ .

13.2 Sample quality

: Ensure that the sample has no bubbles attached and the surface is polished.

13.3 The test room temperature is controlled to

be 20-25°C and the humidity is <60%.

13.4 Safety Protection

Avoid liquid splashing during operation and wear protective glasses.

14 Appendix (Informative Appendix)

Appendix A Typical Density Values

Table A.1 Density of common cemented carbide grades

Brand	Cobalt content (wt %)	Grain size (μm)	Density(g/ cm³)
YG6	6	1-2	14.85-14.95
YG8	8	2-3	14.65-14.75
YG10	10	2-4	14.40-14.50

Appendix B Error Analysis

B.1 Instrument error:

±0.01 g/cm³ (liquid method), ±0.001 g/cm³ (gas method).

B.2 A sample defect

porosity of 0.1% results in a density drop of 0.2 g/ cm³ .

B.3 Environmental influence

temperature ±1°C causes density deviation <0.02%.

Appendix C Improvement Suggestions

C.1 Use a high-precision gas density meter with an error of <±0.0005 g/cm³ . C.2 Use vacuum drying to remove surface bubbles and improve measurement consistency.

C.3 Introduce X-ray tomography (CT) to detect internal pores.

Appendix D Test Data Examples

Table D.1 YG8 cemented carbide density test data

Sample No.	Air quality (g)	Suspended mass (g)	Density(g/ cm³)	Average value (g/ cm³)
YG8-001	5.123	4.578	14.72	14.70
YG8-002	5.126	4.582	14.69	14.70
YG8-003	5.125	4.580	14.70	14.70

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.

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GB/T 18376-2014 Cemented carbide microstructure test method

1 Scope

This standard specifies the preparation, observation and evaluation methods of cemented carbide microstructure. This method is applicable to cemented carbide materials and products (such as YG6, YG8 and other grades) with tungsten carbide (WC) as hard phase and cobalt (Co) as binder phase. The microstructure characteristics, including grain size, phase composition, porosity and defects, are analyzed by optical microscope or scanning electron microscope (SEM). This method can be used for quality control in the production process, product acceptance and performance evaluation in research and development.

This standard does not apply to non-cobalt-based cemented carbides or non-metallic materials.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 3848 Determination of cobalt content in cemented carbide

GB/T 3850-2015 Method for determination of density of cemented carbide

GB/T 13298-2015 Metal microstructure inspection methods

GB/T 4338 Metal microstructure corrosion method

ISO 4499-2:2008 Test methods for microstructure of cemented carbide Part 2: Quantitative phase analysis

ISO 3696 Specification for water for analytical laboratories

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Microstructure

The structural characteristics of cemented carbide at the microscopic scale, including grain size, phase distribution, pores and defects.

3.2 Hardmetal is a composite material made of tungsten carbide (WC)

as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.3 Grain Size

The average diameter of the hard phase (WC) grains, usually in μm .

3.4 Porosity:

The volume fraction of pores in cemented carbide, reflecting the density of the material, with the unit of %.

3.5 η phase (Eta Phase)

is a brittle phase formed due to insufficient carbon content. Its chemical formula is Co_3W_3C , which may affect the performance.

3.6 Free Carbon:

Carbon precipitated due to excessive carbon content, affecting the uniformity of the microstructure.

4 Principle

The inspection of cemented carbide microstructure is carried out by sample preparation, corrosion and microscopic observation to analyze its internal structural characteristics. During the preparation process, the sample is cut, ground, polished, and then the microstructure is analyzed with an etchant (such as Murakami reagent), and then observed using an optical microscope (magnification 100x-1000x) or a scanning electron microscope (SEM). The grain size is measured by the cross-section method, and the porosity and phase composition are quantitatively evaluated by image analysis. The microstructural characteristics are closely related to the sintering process, carbon balance and defects, and can reflect the material properties.

5. Instruments and Equipment

5.1 Optical Microscope

Magnification 100x-1000x, equipped with image analysis system, accuracy ±0.1 μm .

5.2 Scanning Electron Microscopy (SEM)

The resolution is ≤0.1 μm and an energy dispersive spectrometer (EDS) is used for phase analysis.

5.3 Cutting Machine

Equipped with diamond cutting wheel and coolant lubrication to avoid thermal damage.

5.4 Grinding and polishing machine

Equipped with SiC sandpaper (#200-#1200) and diamond suspension (particle size 1-3 μm), surface roughness Ra ≤ 0.05 μm .

5.5 Ultrasonic Cleaner

Used for sample cleaning and removal of residual grinding materials.

5.6 Constant temperature box

Control the drying temperature to 105°C with an accuracy of ±2°C.

6 Reagents

6.1 Deionized water

Conforms to ISO 3696 Grade 1 water standard.

6.2 Murakami reagent

Formula: 10 g $K_3[Fe(CN)_6]$ + 10 g KOH + 100 mL H_2O, corrosion time 5-30 seconds, depending on the sample reaction.

6.3 Ethanol

Analytical grade, concentration ≥99.5%, used for cleaning.

7 Specimens

7.1 Sample requirements

Shape: rectangular or cylindrical, size ≥10 mm × 10 mm × 5 mm, mass ≥5 g.
Surface condition: no cracks (<5 μm), pores (porosity <0.05%) or oxide layer.
Homogeneity: composition deviation <0.1 wt %, grain size fluctuation <5%.
Quantity: No less than 3 samples per batch , highly representative.

7.2 Sample preparation

Cutting: Cutting is done with a diamond cutting wheel perpendicular to the sintering direction, lubricated with coolant, at a speed of <500 rpm.
Grinding: Use #200, #400, #800, and #1200 SiC sandpaper in sequence, apply a pressure of 20-30 N, and the time is 2-3 minutes/level.
Polishing: Use 1-3 μm diamond suspension and flannel cloth for 5-10 minutes, surface Ra ≤ 0.05 μm .
Cleaning and drying: Ultrasonic cleaning with ethanol for 5 min, drying at 105°C for 30 min, and cooling to room temperature.

8 Microstructure display

8.1 Corrosion

Use Murakami reagent to corrode the sample surface for 5-30 seconds (WC is brown, Co is white, and η phase is gray), observe the reaction, and adjust the time if necessary.

After corrosion, rinse with deionized water, dehydrate with ethanol, and dry immediately.

8.2 Inspection

Ensure that the corrosion is uniform without over-corrosion (blurred grain boundaries) or under-corrosion (lack of microstructure).

9 Microstructure inspection

9.1 Observation Methods

Optical microscope: magnification 500x-1000x, observe grain size, phase distribution, pores and defects.

SEM: magnification 1000x-5000x, combined with EDS to analyze phase composition.

9.2 Grain size measurement

According to the cross-section method (ISO 4499-2), 100 WC grains were randomly measured in 10 fields of view, and the diameter was averaged with an accuracy of ± 0.1 μm .

Report the average grain size and distribution range.

9.3 Porosity assessment

According to GB/T 13298-2015 standard, the number and area of pores are counted and classified:

Type A: small pores (<10 μm);

Type B: macropores (10-25 μm);

Type C: aggregates (>25 μm).

Porosity = pore area/total area × 100%, keep 2 decimal places.

9.4 Phase composition analysis

Identify WC, Co, η phase, free carbon, and quantitatively analyze the area percentage of each phase with a deviation of <1%.

9.5 Defect Inspection

Detect cracks and inclusions (such as Fe, Ni), and record their location, size and distribution.

10. Result Expression

The grain size is expressed in μm with one decimal place (e.g. 0.8 μm).

The porosity is expressed in %, with 2 decimal places (eg 0.05%).

Phase composition is expressed as area percentage with one decimal place (e.g. WC 90.5%).

The test report should include:

a) Standard number: GB/T 18376-2014; b) Sample description: brand, batch, size; c) Preparation conditions: cutting, grinding, polishing; d) Observation conditions: magnification, corrosive agent; e) Results: grain size, porosity, phase composition, defects; f) Test date: such as May 21, 2025; g) Tester: signature.

11 Precision and Bias

11.1 Precision

Repeatability: The grain size deviation measured by the same operator and the same equipment is less than 5%, and the porosity deviation is less than 0.02%.

Reproducibility: The grain size deviation measured by different laboratories is <10%, and the porosity deviation is <0.05%.

11.2 Bias

Instrument error: microscope measurement error ±0.1 μm , SEM error <0.01 μm .

Preparation error: Grinding scratches or over-etching can overestimate grain size by 5-10%.

Sample inhomogeneity: composition deviation >0.1 wt % leads to porosity fluctuation of 0.1-0.2%.

12 Influencing factors

12.1 Sintering Process

Temperature (1350-1500°C) affects grain growth, and >1450°C results in coarse grains (>2 μm).

Hot isostatic pressing (HIP, 150 MPa) reduced the porosity (<0.01%).

12.2 Carbon Balance

Insufficient carbon forms η phase (gray, 5-10%), while excess carbon precipitates free carbon (black, <2%).

12.3 Grain size

Fine grains (0.2-0.5 μm) have low porosity (<0.05%), while coarse grains (>5 μm) have high porosity (>0.1%).

12.4 Defects

Inclusions (e.g. Fe 0.1%) lead to local porosity and cracks affecting <0.05 mm.

13 Application of test results

13.1 Quality Control

The grain size is 0.5-1.0 μm and the porosity is <0.05%, which meets the YG6 standard.

13.2 Process Optimization

Porosity > 0.1% indicates insufficient sintering, adjust the temperature (1400°C) or pressure.

13.3 Performance Prediction

Grain refinement (<0.5 μm) increases hardness (HRA >91), while the increase of η phase reduces toughness.

13.4 Examples

YG8 tool, grain size 1.0 μm , porosity 0.03%, ensure cutting life > 3 hours.

14 Notes

14.1 Instrument Calibration

The microscope was calibrated before testing, with an error of <±0.1 μm .

14.2 Sample quality

Ensure that there are no scratches on the surface of the specimen and that the corrosion is uniform.

14.3 Environmental Control

The test room temperature was 20-25°C and the humidity was <60%.

14.4 Security Protection

Wear protective glasses during operation to avoid splashing of corrosive liquid .

15 Appendix (Informative Appendix)

Appendix A Typical Microstructure Parameters

Table A.1 Microstructural characteristics of common cemented carbide grades

Brand	Cobalt content (wt %)	Grain size (μm)	Porosity(%)	Main phase composition (%)
YG6	6	0.6-0.8	0.02-0.05	WC 90, Co 10
YG8	8	0.8-1.0	0.03-0.06	WC 88, Co 12
YG10	10	1.0-1.2	0.04-0.07	WC 86, Co 14

Appendix B Error Analysis

B.1 Instrument error

The microscope measurement error is ±0.1 μm , affecting the grain size by <1%.

B.2 Preparation defects

Over-corrosion causes the porosity to be overestimated by 0.05-0.1%.

B.3 Environmental Impact

Humidity >70% causes surface oxidation, affecting phase recognition.

Appendix C Improvement Suggestions

C.1 Use an automatic image analysis system to improve the accuracy of grain size measurement (<0.05 μm).

C.2 Use SEM-EDS to detect trace η phase, with a quantitative error of <0.5%. C.3 Introduce X-ray diffraction (XRD) to verify the consistency of phase composition.

Appendix D Test Data Examples

Table D.1 YG8 cemented carbide microstructure test data

Sample No.	Grain size (μm)	Porosity(%)	WC (%)	Co (%)	η phase (%)
YG8-001	0.9	0.04	88.2	11.6	0.2
YG8-002	0.8	0.03	88.5	11.4	0.1
YG8-003	0.9	0.05	88.0	11.8	0.2

GB/T 5314-2011 Powders for powder metallurgy Sampling Methods - Chemical Composition

1 Scope

This section specifies the method for determining the chemical composition of powders for powder metallurgy after sampling. This method is applicable to metal powders (such as iron powder, copper powder, tungsten powder, cobalt powder , etc.) and alloy powders for powder metallurgy, and aims to determine their chemical composition through chemical analysis, including the content of main elements (such as Fe, Cu, W, Co, etc.) and impurity elements (such as C, O, S, P, etc.). This method can be used for quality control, production acceptance and component verification in research and development.

This standard does not apply to non-metallic powders or ultrafine nanopowders with a particle size of less than 10 μm (reference should be made to GB/T 33822-2017).

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 223.1 Chemical analysis methods for iron, steel and alloys - Titration method for determination of iron content

GB/T 223.3 Chemical analysis methods for iron, steel and alloys - Determination of phosphorus content - Dianthrone phosphomolybdate gravimetric method

GB/T 223.4 Chemical analysis methods for iron, steel and alloys - Determination of manganese content - Potentiometric titration or visual titration method

GB/T 223.5 Chemical analysis methods for steel and alloys - Determination of silicon content - Silicon- molybdenum blue photometric method

GB/T 223.9 Chemical analysis methods for iron, steel and alloys - Determination of sulfur content - Iodine titration method

GB/T 223.23 Chemical analysis methods for iron, steel and alloys - Determination of cobalt content - Photometric method

GB/T 223.58 Chemical analysis methods for iron, steel and alloys - Determination of tungsten content - Reduction gravimetric method

GB/T 4336 Spark discharge atomic emission spectrometric analysis method for carbon steel and low alloy steel

GB/T 5314-2011 Powder sampling method for powder metallurgy

ISO 4490 General principles for sampling and chemical analysis of metal powders

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Chemical Composition The mass percentage (

wt %) of various elements in powder metallurgy powder , including main elements and impurity elements.

3.2 Sampling

The process of extracting representative samples from a powder batch is carried out in accordance with GB/T 5314-2011.

3.3 Impurity Elements:

trace elements such as carbon (C), oxygen (O), sulfur (S), phosphorus (P), etc. that have an adverse effect on powder properties.

3.4 Powders for Powder Metallurgy

Metal or alloy powders prepared by atomization, reduction or chemical methods and used for pressing and sintering processes.

4 Principle

The determination of chemical composition is done by dissolving or directly analyzing the powder after sampling, and using chemical analysis (such as titration, weight method) or instrumental analysis (such as spectroscopy) to determine the content of each element. The main elements (such as Fe, Cu, W, Co) are quantified by standard methods, and impurity elements (such as C, O) are determined by special instruments. The quality and uniformity of sampling directly affect the accuracy of the results, and the sampling requirements of GB/T 5314-2011 must be strictly followed.

5. Instruments and Equipment

5.1 Analytical balance

Accuracy ±0.0001 g, used for weighing samples.

5.2 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES)

Measurement range: ppm level to wt % level, accuracy ±0.1%.

5.3 Carbon and sulfur analyzer

Determine C and S content with an accuracy of ±0.001 wt %.

5.4 Oxygen and nitrogen analyzer

Determine O and N content with an accuracy of ±0.0005 wt %.

5.5 Titration apparatus

Equipped with potentiometric titrator or automatic titrator, accuracy ±0.01 mL.

5.6 High temperature furnace

Temperature range 1000-1500°C, used for sample melting or combustion.

5.7 Ultrasonic Cleaner

Used for sample cleaning and removal of surface contamination.

6 Reagents

6.1 Nitric acid (HNO_3)

Analytical grade, concentration 65%-68%.

6.2 Hydrochloric acid (HCl)

Analytical grade, concentration 36%-38%.

6.3 Sulfuric acid (H_2SO_4)

Analytical grade, concentration 95%-98%.

6.4 Standard solution

Such as Fe, Cu, W, Co standard solution, concentration 0.01 mol/L, in line with GB/T 601.

6.5 Deionized water

Conforms to ISO 3696 Grade 1 water standard.

6.6 Flux

Such as Na_2CO_3 or Fe powder , used for melting samples.

7 Sampling

7.1 Sampling method

According to GB/T 5314-2011, representative samples are extracted from powder batches using stratified sampling or mechanical sampling.

Sampling points: at least 5 points, mix and package.

7.2 Sample size

Take 50-100 g of total sample from each batch, and 0.5-2 g of sample for analysis.

7.3 Sample Storage

Store in airtight container to avoid oxidation or moisture absorption.

8 Test methods

8.1 Sample preparation

Weigh 0.5-2 g of powder (accuracy ±0.0001 g) and place it in a crucible.

Add an appropriate amount of flux (such as Na_2CO_3 5 g), melt it in a high-temperature furnace at

1000-1200°C for 30 minutes, and dissolve it in dilute acid (HNO_3 : H_2O = 1:1) after cooling. the volume was made up to 100 mL with deionized water .

8.2 Determination of main elements

Iron (Fe): According to GB/T 223.1 titration method, accuracy ±0.01 wt %.
Copper (Cu): According to GB/T 223.7 iodine titration method, accuracy ±0.01 wt %.
Tungsten (W): According to GB/T 223.58 reduction weight method, accuracy ±0.05 wt %.
Cobalt (Co): According to GB/T 223.23 photometric method, accuracy ±0.02 wt %.

8.3 Determination of impurity elements

Carbon (C): using carbon sulfur analyzer , high frequency combustion method, accuracy ±0.001 wt %.
Sulfur (S): Same as carbon sulfur analyzer , accuracy ±0.0005 wt %.
Oxygen (O): using oxygen and nitrogen analyzer, melting-infrared absorption method, accuracy ±0.0005 wt %.
Phosphorus (P): According to GB/T 223.3 dianthrone phosphomolybdate weight method, accuracy ±0.001 wt %.

8.4 Instrumental analysis (optional)

ICP-OES was used to simultaneously determine multiple elements using the calibration curve method with an accuracy of ±0.1% (main element) and ±10 ppm (impurities).
The sample solution is injected directly and the measurement wavelength is selected according to the standard.

8.5 Blank test

Carry out a blank test in the same manner, without adding sample, and deduct the blank value.

8.6 Data Processing

The average of three measurements was taken as the final result.
If the single point deviation is >5% (e.g. Fe 98% changes to 103%), remove it and recalculate.
The results are expressed as wt % with 2 decimal places.

9 Results Expression

The chemical composition is expressed as mass percentage (wt %) with 2 decimal places (e.g. Fe 98.50%, C 0.02%).
The test report should include:
a) Standard number: GB/T 5314-2011;
b) Sample description: powder type, batch, particle size;
c) Sampling method: in accordance with GB/T 5314-2011;
d) Test conditions: temperature, humidity;
e) Instrument model and calibration status;
f) Results: content and deviation of each element;

g) Test date: such as May 21, 2025;
h) Tester: signature.

10 Precision and Bias

10.1 Precision

Repeatability: The composition deviation measured by the same operator and the same equipment is <0.5% (main element) and <0.01% (impurity).
Reproducibility: The composition deviation measured by different laboratories is <1% (main element) and <0.02% (impurity).

10.2 Bias

Instrument error: ICP-OES error ±0.1%, carbon-sulfur instrument error ±0.001%.
Sampling error: Non-uniformity causes deviation of 0.5-1%.
Sample contamination: Surface oxidation causes the oxygen content to be overestimated by 0.01-0.05%.

11 Influencing factors

11.1 Particle size distribution

a particle size of <45 μm are easily oxidized, and the oxygen content increases by 0.02-0.05%.

11.2 Storage conditions

High humidity (>70%) causes surface moisture absorption, affecting C and O determination by 0.01-0.03%.

11.3 Melting Process

Too high a temperature (>1200°C) causes volatilization of elements (e.g. Co loss of 0.1%).

11.4 Sources of Impurities

Low raw material purity (such as Fe impurity S >0.02%) affects the results.

12 Application of test results

12.1 Quality Control

Verify whether the composition meets the specifications, such as Fe powder Fe ≥98%, C ≤0.02%.

12.2 Process Optimization

Oxygen content > 0.1% indicates insufficient reduction, adjust the temperature (800-1000°C).

12.3 Performance Prediction

S content <0.01% and P content <0.02% ensure stable sintering performance.

12.4 Examples

Tungsten powder W ≥99.9%, O <0.05% is used for high-density alloys with a density of 19.2 g/cm³ .

13 Notes

13.1 Instrument Calibration

The analytical instrument was calibrated before testing, with a deviation of <±0.1%.

13.2 Sample quality

Ensure that the specimens are free of contamination and stored dry.

13.3 Environmental Control

The test room temperature was 20-25°C and the humidity was <60%.

13.4 Security Protection

Wear protective glasses during operation to avoid acid splashing.

14 Appendix (Informative Appendix)

Appendix A Typical Chemical Composition Ranges

Table A.1 Chemical composition of common powder metallurgy powders

Powder Type	Main component (wt %)	Upper limit of impurities (wt %)
Iron Fan	Fe ≥98.0	C ≤0.02, O ≤0.1, S ≤0.01
Copper powder	Cu ≥99.0	O ≤0.1, Fe ≤0.1
Tungsten powder	W ≥99.9	C ≤0.01, O ≤0.05
Cobalt powder	Co ≥99.5	Fe ≤0.1, O ≤0.1

Appendix B Error Analysis

B.1 Instrument error

ICP-OES error ±0.1%, impact on main elements <0.1%.

B.2 Sampling error

The inhomogeneity results in a 0.5-1% deviation in Fe.

B.3 Environmental Impact

Humidity >70% overestimated the O content by 0.02%.

Appendix C Improvement Suggestions

C.1 Use vacuum melting method to reduce the deviation of oxygen content determination.

C.2 Use high-precision ICP-MS to detect trace impurities (<1 ppm).

C.3 Introduce automatic sampling system to improve uniformity.

Appendix D Test Data Examples

Table D.1 Iron powder chemical composition test data

Sample No.	Fe (wt %)	C (wt %)	O (wt %)	S (wt %)	Average Fe (wt %)
Fe-001	98.52	0.015	0.082	0.008	98.50
Fe-002	98.48	0.014	0.080	0.007	98.50
Fe-003	98.50	0.016	0.085	0.009	98.50

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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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GB/T 5169-2013 Test method for porosity of cemented carbide

1 Scope

This standard specifies the test method for the porosity of cemented carbide. This method is applicable to cemented carbide materials and products (such as grades YG6, YG8, etc.) with tungsten carbide (WC) as the hard phase and cobalt (Co) as the bonding phase. The porosity (unit: %) is determined by metallographic method or image analysis method, including type A (small pores), type B (large pores) and type C (aggregate) pores. This method can be used for quality control in the production process, product acceptance and performance evaluation in research and development.

This standard does not apply to cemented carbides containing significant non-metallic inclusions or non -cobalt based carbides .

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 18376-2014 Cemented carbide microstructure test method

GB/T 3850-2015 Method for determination of density of cemented carbide

GB/T 13298-2015 Metal microstructure inspection methods

GB/T 4338 Metal microstructure corrosion method

ASTM B276 Determination of apparent porosity of cemented carbide

ISO 4505 Cemented Carbide Microstructure Evaluation Method

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Porosity

The volume fraction of pores in cemented carbide reflects the density of the material. The unit is %, which can be divided into Type A (diameter <10 μm), Type B (diameter 10-25 μm) and Type C (diameter >25 μm).

3.2 Hardmetal is a composite material made of tungsten carbide (WC)

as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy process.

3.3 Metallographic Method:

A method for quantitatively determining porosity through sample preparation, corrosion and microscopic observation.

3.4 Image Analysis Method:

This method uses image processing technology to extract pore data from microscope or scanning electron microscope (SEM) images.

4 Principle

The porosity test of cemented carbide is based on the observation of the cross-sectional microstructure of the sample through an optical microscope or SEM after preparation, and the identification and classification of pores (type A, B, and C). The metallographic method calculates the porosity by manually or automatically counting the number and area of pores; the image analysis method uses software to process image data and automatically measure the pore distribution and percentage. Porosity is closely related to the sintering process, carbon balance, and microstructural uniformity, and affects material properties.

5. Instruments and Equipment

5.1 Optical Microscope

Magnification 100x-1000x, equipped with image analysis system, accuracy ±0.1 μm .

5.2 Scanning Electron Microscopy (SEM)

The resolution is ≤0.1 μm and it is equipped with an energy dispersive spectrometer (EDS) for pore characteristic analysis.

5.3 Cutting Machine

Equipped with diamond cutting wheel and coolant lubrication to avoid thermal damage.

5.4 Grinding and polishing machine

Equipped with SiC sandpaper (#200-#1200) and diamond suspension (particle size 1-3 μm), surface roughness Ra ≤ 0.05 μm .

5.5 Ultrasonic Cleaner

Used for sample cleaning and removal of residual grinding materials.

5.6 Constant temperature box

Control the drying temperature to 105°C with an accuracy of ±2°C.

6 Reagents

6.1 Deionized water

Conforms to ISO 3696 Class I water standard.

6.2 Murakami reagent

Formula: 10 g $K_3[Fe(CN)_6]$ + 10 g KOH + 100 mL H_2O, corrosion time 5-30 seconds, depending on the sample reaction.

6.3 Ethanol

Analytical grade, concentration ≥99.5%, used for cleaning.

7 Specimens

7.1 Sample requirements

Shape: rectangular or cylindrical, size ≥10 mm × 10 mm × 5 mm, mass ≥5 g.
Surface condition: no cracks (<5 μm) or oxide layer, porosity <0.5%.
Homogeneity: composition deviation <0.1 wt %, grain size fluctuation <5%.
Quantity: No less than 3 samples per batch , highly representative.

7.2 Sample preparation

Cutting: Cutting is done with a diamond cutting wheel perpendicular to the sintering direction, lubricated with coolant, at a speed of <500 rpm.
Grinding: Use #200, #400, #800, and #1200 SiC sandpaper in sequence, apply a pressure of 20-30 N, and the time is 2-3 minutes/level.
Polishing: Use 1-3 μm diamond suspension and flannel cloth for 5-10 minutes, surface Ra ≤ 0.05 μm .
Cleaning and drying: Ultrasonic cleaning with ethanol for 5 min, drying at 105°C for 30 min, and cooling to room temperature.

8 Microstructure display

8.1 Corrosion

Use Murakami reagent to corrode the sample surface for 5-30 seconds (WC is brown, Co is white, and pores are black), observe the reaction, and adjust the time if necessary.
After corrosion, rinse with deionized water, dehydrate with ethanol, and dry immediately.

8.2 Inspection

Ensure uniform corrosion without over-corrosion (blurred grain boundaries) or under-corrosion (porosity not revealed).

9 Porosity test

9.1 Metallography

Observation: Use an optical microscope with a magnification of 500x-1000x and observe 10 random fields of view.
Measurement: Manually count the number of A, B, and C type pores and measure the pore area (accuracy ±0.1 μm²) .
Calculation: Porosity = total pore area/total field area × 100%, retain 2 decimal places.

9.2 Image Analysis

Observation: Use SEM or high-resolution optical microscope, magnification 1000x-5000x, take 10 images.

Analysis: Use image processing software (such as ImageJ) to automatically identify pores, classify them into types A, B, and C, and calculate the area percentage.
Verification: Repeat the measurement 3 times and take the average value. The deviation is <0.02%.

9.3 Pore classification

Type A: diameter <10 μm , small pores.
Type B: 10-25 μm in diameter , large pores.
Type C: diameter >25 μm , aggregates.

10. Result Expression

The porosity is expressed in %, with 2 decimal places (eg 0.05%).
The test report should include:
a) Standard number: GB/T 5169-2013;
b) Sample description: brand, batch, size;
c) Preparation conditions: cutting, grinding, polishing;
d) Test method: metallographic method or image analysis method;
e) Result: total porosity and A, B, C type distribution;
f) Test date: such as May 21, 2025;
g) Tester: signature.

11 Precision and Bias

11.1 Precision

Repeatability: The porosity deviation measured by the same operator and the same equipment is <0.02%.
Reproducibility: The porosity deviation between different laboratories is <0.05%.

11.2 Bias

Instrument error: Microscope measurement error ±0.1 μm , impact <0.01%.
Preparation error: Grinding scratches or over-etching can overestimate porosity by 0.02-0.05%.
Specimen inhomogeneity: composition deviation >0.1 wt % leads to porosity fluctuation of 0.1%.

12 Influencing factors

12.1 Sintering Process

Temperature (1350-1500°C) affects the porosity, and >1450°C increases the B and C type pores (>0.1%).
Hot isostatic pressing (HIP, 150 MPa) reduced the total porosity (<0.01%).

12.2 Carbon Balance

Insufficient carbon forms η phase, increasing the porosity by 0.05-0.1%; excess carbon precipitates

free carbon, with an impact of <0.02%.

12.3 Grain size

Fine grains (0.2-0.5 μm) have low porosity (<0.03%), while coarse grains (>5 μm) have high porosity (>0.15%).

12.4 Defects

Inclusions (e.g. Fe 0.1%) lead to a local increase in porosity of 0.05-0.1%.

13 Application of test results

13.1 Quality Control

Porosity <0.05% meets YG6 standard and ensures hardness HRA >90.

13.2 Process Optimization

Porosity > 0.1% indicates insufficient sintering, adjust the temperature (1400°C) or pressure.

13.3 Performance Prediction

Porosity <0.03% corresponds to high flexural strength (>2000 MPa), >0.1% reduces toughness.

13.4 Examples

YG8 tool, porosity 0.04%, cutting life >3 hours.

14 Notes

14.1 Instrument Calibration

The microscope was calibrated before testing, with an error of <±0.1 μm .

14.2 Sample quality

Ensure that there are no scratches on the surface of the specimen and that the corrosion is uniform.

14.3 Environmental Control

The test room temperature was 20-25°C and the humidity was <60%.

14.4 Security Protection

Wear protective glasses during operation to avoid splashing of corrosive liquid .

15 Appendix (Informative Appendix)

Appendix A Typical porosity range

Table A.1 Porosity of common cemented carbide grades

Brand	Cobalt content (wt %)	Grain size (μm)	Porosity(%)
YG6	6	0.6-0.8	0.02-0.05
YG8	8	0.8-1.0	0.03-0.06
YG10	10	1.0-1.2	0.04-0.07

Appendix B Error Analysis

B.1 Instrument error

The microscope measurement error is ±0.1 μm , affecting the porosity by <0.01%.

B.2 Preparation defects

Over-corrosion causes the porosity to be overestimated by 0.02-0.05%.

B.3 Environmental Impact

Humidity >70% causes surface oxidation, affecting the measurement by 0.01%.

Appendix C Improvement Suggestions

C.1 Use X-ray tomography (CT) to detect internal porosity with an accuracy of <0.01%.

C.2 Use an automatic image analysis system to improve the consistency of porosity measurement.

C.3 Introduce a vacuum sintering process to reduce initial porosity.

Appendix D Test Data Examples

Table D.1 Test data of porosity of YG8 cemented carbide

Sample No.	Type A(%)	Type B(%)	Type C (%)	Total porosity (%)	average value(%)
YG8-001	0.02	0.01	0.00	0.03	0.04
YG8-002	0.03	0.01	0.01	0.05	0.04
YG8-003	0.02	0.02	0.00	0.04	0.04

GB/T 12444-2006 Test methods for wear resistance of metals and alloys

1 Scope

This standard specifies the test method for the wear resistance of metals and alloys. This method is applicable to metal and alloy materials (such as steel, aluminum alloy, copper alloy, etc.) and their surface coatings. Through wear tests under laboratory controlled conditions, the wear resistance of materials is evaluated, including low stress wear (scratching wear), high stress wear (impact wear) and sliding wear. This method can be used for material selection, quality control, production acceptance and wear resistance evaluation in research and development.

This standard is not applicable to non-metallic materials or wear in extreme environments (such as high temperatures > 1000°C or highly corrosive environments).

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 6394 Metal test specimen dimensions and preparation methods

GB/T 10610 Determination of surface roughness of metallic materials

GB/T 13298-2015 Metal microstructure inspection methods

ASTM G65 Standard Test Method for Dry Sand /Rubber Wheel Abrasion Test

ASTM D4060 Standard test method for abrasion resistance of organic coatings using the Taber abrader

ISO 8251 Determination of wear resistance of anodic oxide coatings on aluminium and its alloys

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Wear Resistance

The ability of a metal or alloy to resist surface material loss under specific wear conditions, usually characterized by mass loss, volume loss or wear depth.

3.2 Low-Stress Abrasion:

Wear caused by slight scratching or sliding, common in low-load, low-impact wear environments.

3.3 High-Stress Abrasion:

Wear caused by high load or impact, often accompanied by plastic deformation or fracture of the material surface.

3.4 Sliding Wear

Material loss caused by friction when two surfaces slide relative to each other.

3.5 Wear Rate

The amount of material loss per unit time or unit sliding distance, expressed in g/m or mm^3 / N · m .

4 Principle

The wear resistance of metals and alloys is evaluated by wear tests under controlled laboratory conditions. Test methods include dry sand /rubber wheel test (low stress wear), Taber abrasion test (sliding wear) and impact wear test, which simulate different wear mechanisms. Wear resistance is characterized by measuring the mass loss, volume loss or wear depth of the specimen before and after the test. Test conditions (such as load, speed, abrasive type) directly affect the results and need to be strictly controlled.

5. Instruments and Equipment

5.1 Analytical balance

Accuracy: ±0.0001 g, used to weigh sample mass.

5.2 Dry sand /rubber wheel testing machine

Meets ASTM G65 requirements, rubber wheel hardness 60-70 Shore A, sand flow rate 300-400 g/min.

5.3 Taber Abrasion Tester

Meets ASTM D4060 requirements with CS-17 or H-18 grinding wheels, 500-1000 g load.

5.4 Impact wear testing machine

Simulate high stress wear, impact frequency 50-100 times/min, load 10-50N.

5.5 Microscope

Magnification 50x-500x, used to observe wear morphology.

5.6 Surface Roughness Tester

Comply with GB/T 10610, measuring range Ra 0.01-10 μm .

6 Reagents and Materials

6.1 Standard abrasives

Dry sand: natural quartz sand, particle size 50-70 mesh, in accordance with ASTM G65.
Taber wheels: CS-17 (medium hardness) or H-18 (high hardness).

6.2 Ethanol

Analytical grade, concentration ≥99.5%, used for cleaning.

6.3 Deionized water

Conforms to ISO 3696 Grade 1 water standard.

7 Specimens

7.1 Sample requirements

Shape: Rectangular or circular, dimensions 76 mm × 25 mm × 6 mm (dry sand /rubber wheel test) or 100 mm diameter × 3 mm thickness (Taber test).

Surface condition: smooth surface, no cracks, roughness Ra ≤ 0.8 μm .

Quantity: At least 3 specimens for each condition .

Homogeneity: Composition deviation <0.1 wt %.

7.2 Sample preparation

The specimens were cut according to GB/T 6394 and the surfaces were ground with #600-#1200 SiC sandpaper.

The samples were ultrasonically cleaned with ethanol for 5 min and weighed (±0.0001 g) after drying.

8 Test methods

8.1 Dry sand /rubber wheel test (low stress wear)

8.1.1 Test conditions

Load: 130 N.

Sand flow rate: 300-400 g/min.

Test time: 6000 rpm (about 30 minutes).

Environment: Temperature 23±2°C, humidity 50±5%.

8.1.2 Test steps

Fix the sample on the testing machine fixture and adjust the rubber wheel to contact the sample.

Start the sand flow, rotate the rubber wheel, and record the mass at the beginning of the test (W_1).

After the test, remove the sample, clean and dry it, and weigh it (W_2).

Calculate the mass loss: $\Delta W = W_1 - W_2$

The measurement was repeated 3 times and the average value was taken with a deviation of <5%.

8.2 Taber wear test (sliding wear)

8.2.1 Test conditions

Grinding wheel: CS-17 (medium wear).

Load: 1000 g.

Rotation speed: 60 rpm.

Test cycle: 10000 revolutions.

Environment: Temperature 23±2°C, humidity 50±5%.

8.2.2 Test steps

Fix the sample on the turntable of the Taber testing machine and install the grinding wheel.

Record the mass at the start of the test (W_1).

Start the testing machine, run it at 10,000 revolutions, and clean the grinding debris regularly.

After the test, clean the sample and weigh it (W_2).

Calculate the mass loss: $\text{磨耗指数} = \frac{\Delta W}{\text{试样数}} \times 1000$

The measurement was repeated 3 times and the average value was taken with a deviation of <5%.

8.3 Impact wear test (high stress wear)

8.3.1 Test conditions

Load: 20 N.

Impact frequency: 60 times/min.

Test duration: 30 minutes.

Environment: Temperature 23±2°C, humidity 50±5%.

8.3.2 Test steps

Fix the sample on the fixture of the impact tester and adjust the position of the impact head.

Record the mass at the start of the test (W_1).

Start the testing machine, run it for 30 minutes, and record the number of impacts.

After the test, clean the sample and weigh it (W_2).

Calculate the mass loss: $\Delta W = W_1 - W_2$

The measurement was repeated 3 times and the average value was taken with a deviation of <5%.

9 Results Expression

The mass loss is expressed in grams with four decimal places (eg 0.0123 g).

The wear index is expressed in mg/1000 revolutions, with one decimal place (eg 1.2 mg/1000 revolutions).

The test report should include:

a) Standard number: GB/T 12444-2006;

b) Sample description: material brand, size, surface condition;

c) Test method: dry sand /rubber wheel, Taber abrasion or impact wear;

d) Test conditions: load, speed, abrasive type;

e) Result: mass loss or wear index;

f) Test date: such as May 21, 2025;

g) Tester: signature.

10 Precision and Bias

10.1 Precision

Repeatability: The deviation of mass loss measured by the same operator and the same equipment is <5%.
Reproducibility: The deviation of mass loss measured by different laboratories is <10%.

10.2 Bias

Instrument error: balance error ±0.0001 g, influence <1%.
Abrasive deviation: Grit non-uniformity causes mass loss to fluctuate by 2-5%.
Environmental influence: Humidity >60% causes surface oxidation, affecting <2%.

11 Influencing factors

11.1 Material hardness

High hardness (such as HRC >60) has good wear resistance and reduces mass loss by 10-20%.

11.2 Surface roughness

Ra >1.0 μm increases wear and mass loss by 5-10%.

11.3 Abrasive properties

Increasing the sand particle size (>70 mesh) increases wear and increases mass loss by 10-15%.

11.4 Test conditions

Increasing the load (130 N to 150 N) increased the mass loss by 5-8%.

12 Application of test results

12.1 Material Selection

Mass loss <0.01 g Meets high wear resistance requirements and is suitable for mining equipment.

12.2 Process Optimization

Mass loss > 0.05 g indicates insufficient heat treatment and the quenching temperature should be adjusted (900°C).

12.3 Performance Prediction

A wear index of <1.5 mg/1000 revolutions corresponds to a service life of >10 years.

12.4 Examples

45# steel, dry sand test mass loss 0.008 g, used for excavator bucket, life span>5000 hours.

13 Notes

13.1 Instrument Calibration

The testing machine was calibrated before testing, and the load deviation was <±1%.

13.2 Sample quality

Ensure that the surface of the specimen is clean and has a uniform roughness.

13.3 Environmental Control

The test room temperature was 23±2°C and the humidity was 50±5%.

13.4 Security Protection

Wear protective glasses during operation to avoid sand splashing.

14 Appendix (Informative Appendix)

Appendix A Typical Wear Resistance Data

Table A.1 Mass loss of common metals and alloys

Material	Test methods	Mass loss (g)	Wear index (mg/1000 revolutions)
45# Steel	Dry sand /rubber wheel	0.008	-
304 Stainless Steel	Taber Wear	0.012	1.2
Aluminum Alloy 6061	Impact wear	0.015	-

Appendix B Error Analysis

B.1 Instrument error

The balance error is ±0.0001 g, and the influence is <1%.

B.2 Abrasive Deviation

The inhomogeneity of the sand particles causes the mass loss to fluctuate by 2-5%.

B.3 Environmental Impact

Humidity >60% causes surface oxidation, affecting <2%.

Appendix C Improvement Suggestions

C.1 Use laser microscope to accurately measure wear depth (<0.01 μm).

C.2 Use standardized abrasives to reduce deviation.

C.3 Introduce real-time monitoring system to improve test consistency.

Appendix D Test Data Examples

Table D.1 45# steel dry sand /rubber wheel test data

Sample No.	Mass before test (g)	Mass after test (g)	Mass loss (g)	Average value (g)
45#-001	50.1234	50.1156	0.0078	0.0080
45#-002	50.1250	50.1169	0.0081	0.0080
45#-003	50.1242	50.1160	0.0082	0.0080

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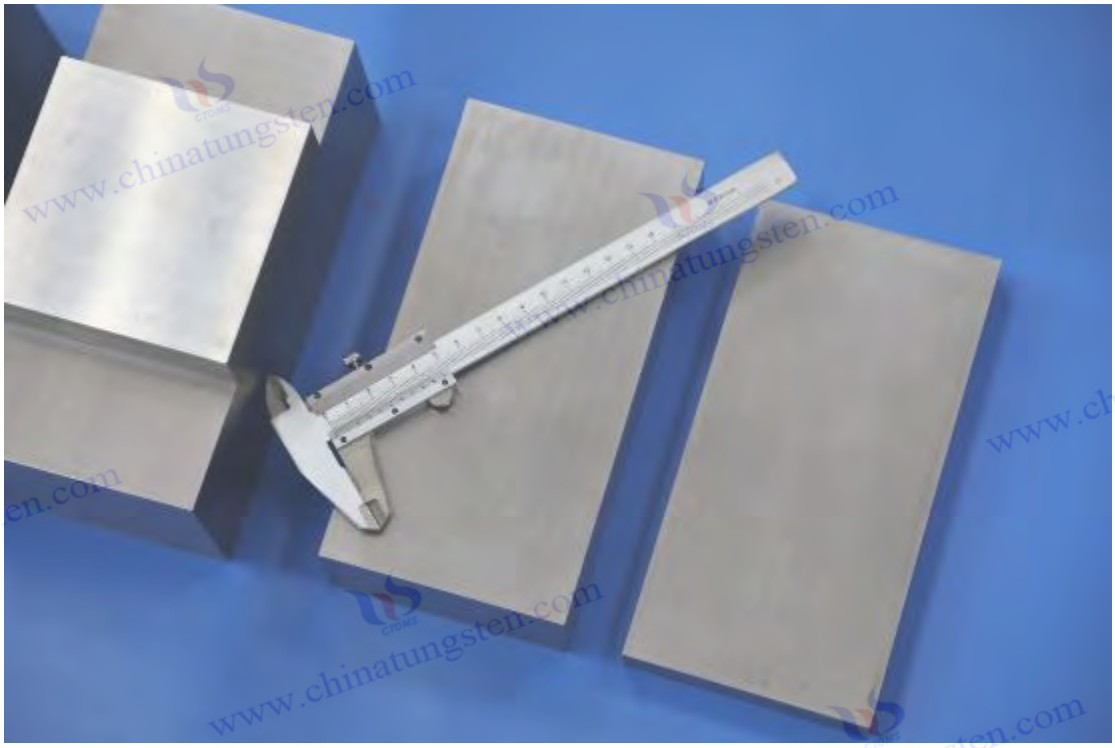


GB/T 1482-2010 Determination of flowability of metal powders Hall flow meter method

1 Scope

This standard specifies the method for determining the fluidity of metal powders using the Hall flowmeter method. This method is applicable to metal powders that can flow freely through a standard funnel with a hole diameter of 2.5 mm. The time (unit: second) required for 50 g of powder to flow through the standard funnel is measured to characterize the fluidity of the powder. This method can be used for quality control, production acceptance and fluidity evaluation in R&D of powder metallurgy, additive manufacturing (such as 3D printing SLM, EBM process) and related fields.

This standard is not applicable to powders that are not free-flowing (such as ultrafine powders with a particle size of <10 μm or highly adhesive powders).

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 5314-2011 Powder sampling method for powder metallurgy

GB/T 1479.1-2010 Determination of bulk density of metal powders Part 1: Funnel method

GB/T 31057.3-2008 Physical properties of granular materials Part 3: Flowability index

ISO 4490:2008 Determination of flow properties of metal powders using a calibrated funnel (Hall rheometer)

ASTM B213-17 Standard method for determining flow rate of metal powders using a Hall flowmeter funnel

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Fluidity

The ability of metal powder to flow freely under specified conditions, characterized by the time (seconds) required for 50 g of powder to flow through a standard funnel (pore size 2.5 mm), with the unit of s/50 g.

3.2 Hall Flowmeter:

An instrument used to measure the fluidity of metal powders. It consists of a standard funnel, a receiving container and a timing device.

3.3 Metal Powder

Metal or alloy particles prepared by atomization, reduction or chemical methods, used in powder metallurgy or additive manufacturing .

3.4 Free Flowing:

The powder can flow continuously through a standard funnel without any external force (gravity alone).

4 Principle

The Hall flow meter method characterizes the flowability of a metal powder by measuring the time it takes for 50 g of the powder to flow through a standard funnel with a hole diameter of 2.5 mm. The flowability is affected by the physical properties of the powder, such as particle size, shape, surface state, adhesion and friction. The shorter the flow time, the better the flowability. The test needs to be carried out under controlled environmental conditions to ensure the repeatability and accuracy of the results.

5. Instruments and Equipment

5.1 Hall flow meter

Funnel: Made of non-magnetic, corrosion-resistant metal (such as stainless steel), with polished inner wall and roughness Ra ≤ 0.4 μm .

Funnel geometric parameters: top diameter 60 mm, bottom aperture 2.5±0.02 mm, cone angle 60°±0.5°.

Height: 100±2 mm from bottom hole to top .

5.2 Receiving container

Volume ≥100 mL, diameter ≥39 mm, used to receive the outflowing powder.

5.3 Analytical balance

Measuring range ≥100 g, accuracy ±0.01 g.

5.4 Stopwatch

Accuracy ±0.2 s, used for timing.

5.5 Ultrasonic Cleaner

For cleaning funnels and containers.

5.6 Drying oven

Temperature control range 105±2°C for drying powder.

6 Reagents

6.1 Ethanol

Analytical grade, concentration ≥99.5%, used for cleaning.

6.2 Deionized water

Conforms to ISO 3696 Grade 1 water standard.

7 Specimens

7.1 Sample requirements

Sample volume: at least 200 g, able to flow freely through a 2.5 mm pore funnel.
Particle size: typically 10-150 μm , depending on powder type.
Uniformity: Particle size distribution deviation <5%, avoid agglomeration or stratification.
Quantity: Each batch shall be divided into 3 portions after sampling, each portion shall be ≥ 50 g.

7.2 Sample preparation

Samples were taken from the powder batch according to GB/T 5314-2011 to ensure representativeness.
Place the sample in a drying oven (105±2°C) and dry for 30 minutes, then cool to room temperature.
If there is oil on the powder surface, use ethanol ultrasonic cleaning for 5 minutes and use it after drying.

8 Test methods

8.1 Test conditions

Ambient temperature: 23±2°C.
Relative humidity: 50±5%, avoid powder absorbing moisture.
Test area: No airflow interference, the instrument is placed on a horizontal surface.

8.2 Instrument Calibration

Check the funnel aperture (2.5 ± 0.02 mm) to ensure that there is no blockage or deformation.
The instrument was calibrated with standard powder (pure spherical powder with known flow rate, such as outflow time 30 ± 1 s/50 g) with a deviation of < ± 2%.

8.3 Test procedures

Weigh 50±0.01 g of sample and record the mass (m).
Temporarily close the hole at the bottom of the funnel with your finger or a baffle, and pour the sample into the funnel to ensure that the powder is evenly distributed.
Start the stopwatch and simultaneously remove the baffle to allow the powder to flow freely.
When the powder has completely flowed out (no residue in the funnel), stop timing and record the outflow time (t, unit: seconds).
Each sample was measured 3 times and the average value was taken with a deviation of <±2 s.
If the powder cannot flow out or is blocked midway, record it as "unable to flow".

8.4 Data Processing

Fluidity is expressed as outflow time (s/50 g) with one decimal place (e.g. 32.5 s/50 g).
If the deviation of the three measurements was >2 s, the outliers were eliminated and the test was repeated.

9 Results Expression

The fluidity is expressed as outflow time (s/50 g) with one decimal place.
The test report should include:
a) Standard number: GB/T 1482-2010;
b) Sample description: powder type, batch, particle size distribution;
c) Test conditions: temperature, humidity;
d) Instrument status: funnel aperture, calibration;
e) Results: average outflow time and deviation;
f) Test date: such as May 21, 2025;
g) Tester: signature.

10 Precision and Bias

10.1 Precision

Repeatability: The outflow time deviation measured by the same operator and the same equipment is <±2 s.
Reproducibility: The deviation of outflow time measured by different laboratories is <±3 s.

10.2 Bias

Instrument error: funnel aperture deviation ±0.02 mm, impact time <±1 s.
Powder state: moisture absorption or agglomeration will extend the outflow time by 2-5 s.
Operational error: uneven pouring or timing deviation affects <±1 s.

11 Influencing factors

11.1 Particle size distribution

Particle size <45 μm increases adhesion and prolongs the outflow time by 5-10 s; particle size >150 μm has good fluidity and shortens the time by 3-5 s.

11.2 Particle shape

Spherical powders (such as those produced by AEM Deposition, with a flow time of <35 s/50 g) flow better than irregular shapes (5-10 s longer).

11.3 Surface conditions

A rough surface or satellite balls (small particles attached) will extend the outflow time by 3-8 seconds.

11.4 Environmental conditions

Humidity >60% causes the powder to absorb moisture and the outflow time is prolonged by 2-5 s.

11.5 Powder properties

High adhesion or friction (such as fine powders or oxidized surfaces) results in poor flow and may not flow.

12 Application of test results

12.1 Quality Control

The outflow time <35 s/50 g meets the 3D printing SLM process requirements.

12.2 Process Optimization

Outflow time >40 s/50 g indicates that the particle shape is poor and the atomization process needs to be optimized.

12.3 Performance Prediction

Outflow time <30 s/50 g corresponds to good uniform powder spreading performance and a printing defect rate of <1%.

12.4 Examples

Titanium alloy powder (Ti-6Al-4V), flow time 32.5 s/50 g, used for printing aviation parts, surface roughness Ra <5 μm .

13 Notes

13.1 Instrument Calibration

The funnel aperture and stopwatch were calibrated before testing, with a deviation of <±1%.

13.2 Sample quality

Make sure the specimen is dry and free of agglomerates.

13.3 Environmental Control

The test room temperature was 23±2°C and the humidity was 50±5%.

13.4 Security Protection

Avoid powder flying during operation and wear a protective mask.

14 Appendix (Informative Appendix)

Appendix A Typical Liquidity Data

Table A.1 Flow time of common metal powders

Powder Type	Particle size (μm)	Particle shape	Flow time (s/50 g)
Titanium alloy powder	15-45	spherical	30.0-35.0
Stainless steel powder	20-63	spherical	28.0-33.0
Copper powder	45-100	irregular	35.0-40.0

Appendix B Error Analysis

B.1 Instrument error

A funnel aperture deviation of ±0.02 mm affects the outflow time by <±1 s.

B.2 Powder state

Moisture absorption prolongs the efflux time by 2-5 s.

B.3 Environmental Impact

Humidity >60% increases the effluent time by 2-3 s.

Appendix C Improvement Suggestions

C.1 Use an automatic timing system to reduce manual timing errors.

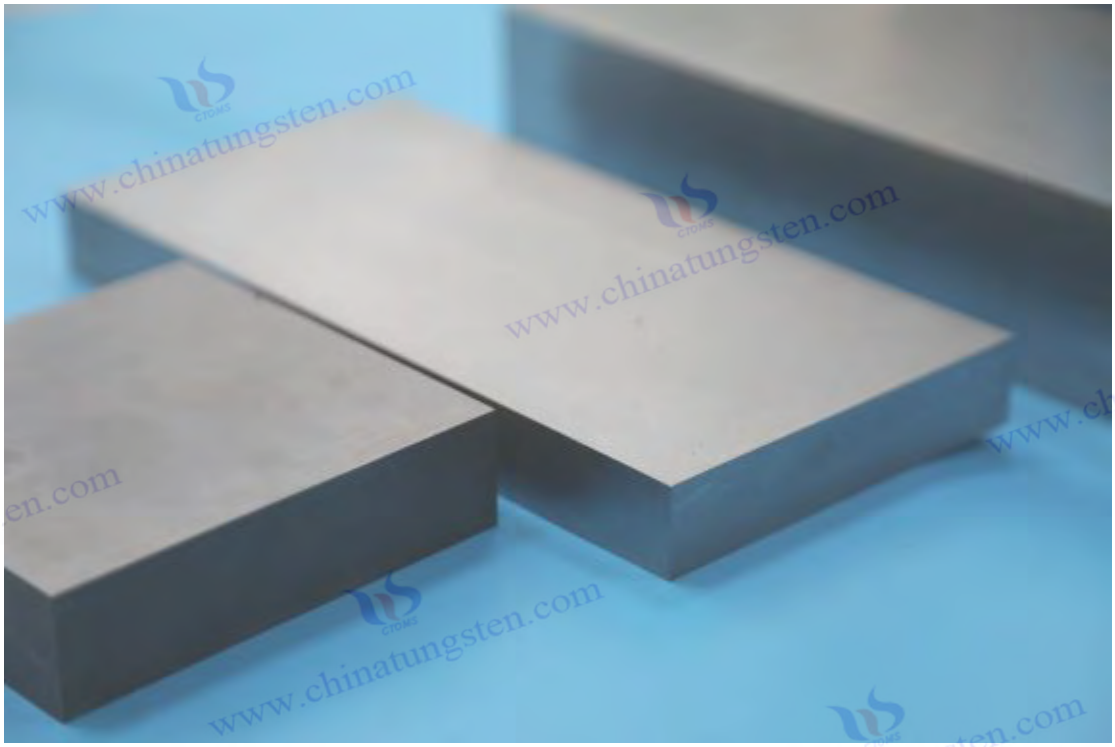
C.2 Use a laser particle size analyzer to accurately control particle size distribution.

C.3 Introduce a vibration device to improve the fluidity of highly adhesive powders.

Appendix D Test Data Examples

Table D.1 Stainless steel powder fluidity test data

Sample No.	Mass(g)	Flow time(s)	Average outflow time (s/50 g)
SS-001	50.02	32.8	32.5
SS-002	50.01	32.4	32.5
SS-003	50.00	32.3	32.5



GB/T 5243-2008 Method for marking properties of cemented carbide grades

1 Scope

This standard specifies the marking method for cemented carbide grade performance. This method is applicable to cemented carbide (including YG, YT, and YW series grades) with tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase. Its performance parameters, including chemical composition, physical properties, and mechanical properties, are clarified through a unified marking method. This standard can be used for material selection, quality control, production acceptance, and grade performance management in research and development.

This standard does not apply to non-cobalt-based cemented carbides or non-WC-based cemented carbides.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 18376-2014 Cemented carbide microstructure test method

GB/T 3850-2015 Method for determination of density of cemented carbide

GB/T 5169-2013 Test method for porosity of cemented carbide

GB/T 5242-2006 Cemented Carbide Grade Classification and Application Guide

ISO 4499-1 Methods for determination of physical properties of cemented carbide Part 1: Density

ISO 4499-2 Methods for determination of mechanical properties of cemented carbide Part 2: Hardness

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Hardmetal is a composite material made of tungsten carbide (WC **)** as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy.

3.2 Grade

The identification code of cemented carbide reflects its chemical composition, physical properties and mechanical properties, and is used to distinguish materials for different purposes.

3.3 Chemical Composition

The mass percentage (wt %) of each element in cemented carbide, including WC, Co and added elements (such as TiC , TaC).

3.4 Physical Properties:

Density, porosity, grain size and other properties of cemented carbide.

3.5 Mechanical Properties:

Hardness, bending strength, toughness and other properties of cemented carbide.

4. Brand performance marking method

4.1 Brand naming rules

Cemented carbide grades are represented by a combination of letters and numbers, following the following rules:

First letter: Indicates the application category

YG: General purpose cemented carbide (WC-Co alloy).

Cemented carbide containing titanium carbide (TiC) with high wear resistance.

Cemented carbide containing tantalum carbide (TaC) or niobium carbide (NbC) with excellent comprehensive performance.

Number: Indicates the cobalt (Co) content (wt %), such as YG6 means the cobalt content is 6%.

Suffix (optional): indicates special performance or use

K: For cutting (such as YG6K).

M: For impact resistance (such as YG8M).

F: Fine grains (such as YG6F).

4.2 Performance parameter marking

The performance of the brand shall include the following parameters, marked in a fixed format:

Chemical composition: WC content, Co content, added element content (wt %).

Physical properties: density (g/cm^3) , porosity (%), grain size (μm).

Mechanical properties: hardness (HRA), flexural strength (MPa), fracture toughness ($MPa \cdot m^{1/2}$).

4.3 Annotation Format

The performance of the grades is marked in table form, for example:

Brand: YG6

Chemical composition: WC 94%, Co 6%

Physical properties: density 14.9 g/cm³ , porosity <0.05%, grain size 0.8-1.0 μm

Mechanical properties: hardness 91.5 HRA, flexural strength 2200 MPa, fracture toughness 10.5 MPa·m $^{1/2}$

5 Test methods

5.1 Chemical composition determination

After sampling according to GB/T 5314-2011, the contents of WC, Co and added elements were determined by chemical analysis with an accuracy of ±0.1 wt %.

5.2 Physical properties determination

Density: According to GB/T 3850-2015, accuracy ±0.01 g/ cm³ .

Porosity: According to GB/T 5169-2013, metallographic method or image analysis method, accuracy ±0.01%.

Grain size: According to GB/T 18376-2014, measured by metallographic microscope, accuracy ±0.1 μm .

5.3 Mechanical properties determination

Hardness: According to ISO 4499-2, Vickers hardness (HV) or Rockwell hardness (HRA), accuracy ±0.5 HRA.

Bending strength: According to ISO 3327, three-point bending method, accuracy ±50 MPa.

Fracture toughness: According to single edge notched beam method (SENB), accuracy ±0.5 MPa·m $^{1/2}$.

6 Results Expression

The performance of the grades is listed in a table, with the parameter values retained to the specified decimal places:

Chemical composition: keep 1 decimal place (eg 94.0%).

Density: Keep 2 decimal places (e.g. 14.90 g/cm³) .

Porosity: keep 2 decimal places (eg 0.05%).

Grain size: keep 1 decimal place (such as 1.0 μm).

Hardness: Keep 1 decimal place (eg 91.5 HRA).

Flexural strength: retain integers (such as 2200 MPa).

Fracture toughness: keep one decimal place (e.g. 10.5 MPa·m $^{1/2}$).

The test report should include:

a) Standard number: GB/T 5243-2008;

b) Brand: such as YG6;
c) Sample description: batch, size;
d) Test method: chemical composition, physical properties, mechanical properties;
e) Results: performance parameter table;
f) Test date: such as May 21, 2025;
g) Tester: signature.

7 Precision and bias

7.1 Precision

Chemical composition: Repeatability deviation <±0.1 wt %.
Physical properties: Density deviation <±0.01 g/cm³ , porosity deviation <±0.02%.
Mechanical properties: hardness deviation <±0.5 HRA, flexural strength deviation <±50 MPa.

7.2 Bias

Instrument error: balance error ±0.0001 g, microscope error ±0.1 μm .
Specimen inhomogeneity: Composition deviation >0.1 wt % affects flexural strength fluctuation by ±100 MPa.
Environmental influence: Humidity >70% overestimates porosity by 0.01-0.03%.

8 Influencing factors

8.1 Composition Fluctuation

cobalt content of ±0.5% will cause a change in hardness of ±1 HRA and a change in flexural strength of ±200 MPa.

8.2 Grain size

Grain size <0.5 μm increases hardness (>92 HRA) and decreases toughness (<9 MPa·m $^{1/2}$); grain size >2 μm decreases hardness (<90 HRA) and increases toughness (>12 MPa·m $^{1/2}$).

8.3 Sintering process

Temperature >1450°C increases porosity (>0.1%) and reduces flexural strength by 100-300 MPa.

8.4 Adding Elements

TiC >5% increases hardness (+1 HRA) and decreases toughness (-1 MPa·m $^{1/2}$).

9 Application of Grade Performance

9.1 Material selection

YG6 (hardness 91.5 HRA, bending strength 2200 MPa) is suitable for cutting tools.

9.2 Process Optimization

Bending strength <2000 MPa indicates that the sintering temperature is insufficient and should be adjusted to 1400-1450°C.

9.3 Performance Prediction

Hardness>91 HRA, toughness>10 MPa·m $^{1/2}$ corresponds to cutting life>5 hours.

9.4 Examples

YG8 (bending strength 2400 MPa, toughness 11.0 MPa·m $^{1/2}$), used for impact drill bits, life span >3000 impacts.

10. Notes

10.1 Instrument Calibration

The balance and microscope were calibrated before testing, with a deviation of <±1%.

10.2 Sample quality

Ensure that the specimen is free of cracks and has uniform composition.

10.3 Environmental Control

The test room temperature was 20-25°C and the humidity was <60%.

10.4 Security Protection

Wear protective glasses during operation to avoid powder flying.

11 Appendix (Informative Appendix)

Appendix A Properties of Common Cemented Carbide Grades

Table A.1 Typical grades properties

Brand	WC (wt %)	Co (wt %)	Density(g/ cm³)	Porosity(%)	Grain size (μm)	Hardness (HRA)	Flexural strength(MPa)	Fracture toughness (MPa·m $^{1/2}$)
YG6	94.0	6.0	14.90	0.04	0.8-1.0	91.5	2200	10.5
YG8	92.0	8.0	14.70	0.05	1.0-1.2	90.5	2400	11.0
YT15	79.0	6.0	12.50	0.03	0.6-0.8	92.0	1800	9.0

Appendix B Error Analysis

B.1 Instrument error

Balance error ±0.0001 g affects density <0.01 g/ cm³ .

B.2 Sample deviation

The uneven composition causes the flexural strength to fluctuate by ±100 MPa.

B.3 Environmental Impact

Humidity >70% overestimates porosity by 0.01-0.03%.

Appendix C Improvement Suggestions

C.1 X-ray fluorescence (XRF) is used to analyze the composition with an accuracy of <±0.05 wt %.

C.2 Scanning electron microscope (SEM) is used to measure the grain size with an accuracy of <±0.05 μm .

C.3 An automated testing system is introduced to improve measurement consistency.

Appendix D Test Data Examples

Table D.1 YG6 grade performance test data

parameter	Measurement 1	Measurement 2	Measurement 3	average value
Density(g/ cm^3)	14.91	14.89	14.90	14.90
Hardness (HRA)	91.4	91.6	91.5	91.5
Flexural strength(MPa)	2180	2220	2200	2200

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GB/T 34505-2017
Additive Manufacturing Metal powder Preparation method specifications

1 Scope

This standard specifies the preparation method specifications for metal powders for additive manufacturing , including raw material selection, preparation process, quality control and performance requirements. This method is applicable to metal powders (such as titanium alloys, aluminum alloys, stainless steel, etc.) used in additive manufacturing (such as selective laser melting SLM, electron beam melting EBM, etc.) to ensure that the particle size distribution, morphology, fluidity and chemical composition of the powder meet the requirements of the additive manufacturing process. This standard can be used for guidance of the powder preparation process, production acceptance and performance verification.

This standard does not apply to non-metallic powders or metal powders not intended for additive manufacturing.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 1482-2010 Determination of the fluidity of metal powders - Hall rheometer method

GB/T 5314-2011 Powder sampling method for powder metallurgy

GB/T 13305 Chemical analysis methods for steel and ferroalloys

GB/T 19077.1-2008 Particle size distribution measurement by laser diffraction method Part 1: General

ISO 13320-1:2009 Particle size analysis by laser diffraction

ASTM B214-16 Determination of bulk density of metal powders

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Additive Manufacturing (AM)

is a technology that manufactures entities by depositing materials layer by layer, including SLM, EBM, etc.

3.2 Metal Powder

Metal or alloy particles prepared by a specific process and used as raw materials for additive manufacturing .

3.3 Preparation Method: The process

of processing metal raw materials into powders that meet the requirements of additive manufacturing , including atomization method, mechanical crushing method, etc.

3.4 Particle Size Distribution

The statistical distribution of powder particle size, usually expressed as D10, D50, or D90.

3.5 Sphericity:

The degree to which powder particles are close to spherical shape, which affects the uniformity and fluidity of powder spreading.

4 Preparation method

4.1 Raw material selection

Material type: Use high-purity metals or alloys (such as Ti-6Al-4V, 316L stainless steel) with impurity content ≤ 0.1 wt %.

Initial form: Metal rod, wire or sponge metal (such as titanium sponge).

Purity requirements: oxygen content ≤ 0.2 wt %, nitrogen content ≤ 0.05 wt %.

4.2 Preparation process

4.2.1 Gas Atomization

Principle: The molten metal is sprayed into fine droplets through high-pressure gas (such as nitrogen or argon) and cooled into spherical powder.

Process parameters:

Melting temperature: 1500-1800°C (depending on the material).

Gas pressure: 2-5 MPa.

Cooling rate: 10^3 -10^5 K /s .

Applicable materials: titanium alloy, nickel-based alloy.

Output characteristics: particle size 10-150 μm , sphericity>0.9.

4.2.2 Plasma Rotating Electrode Process (PREP)

Principle: After the rotating electrode is melted, it forms droplets through centrifugal force and cools into powder.

Process parameters:

Electrode rotation speed: 10000-20000 rpm.

Power: 50-100 kW.

Cooling medium: Argon or helium.

Applicable materials: high melting point metals (such as tungsten and molybdenum).

Output characteristics: particle size 20-200 μm , sphericity>0.95, oxygen content<0.1 wt %.

4.2.3 Mechanical Alloying

Principle: Metal powders are mixed and refined by high-energy ball milling.

Process parameters:

Ball milling time: 10-50 hours.

Ball to material ratio: 10:1 to 20:1.
Rotation speed: 300-500 rpm.
Applicable materials: aluminum-based composite materials.
Output characteristics: particle size 1-50 μm , irregular morphology.

4.2.4 Dissolution-Precipitation Method

Principle: The metal is dissolved and then precipitated into powder under controlled conditions.
Process parameters:
Dissolving temperature: 150-200°C.
Pressure: 0.5-1.0 MPa.
Solid-liquid ratio : 0.05-0.1 g/ml.
Applicable materials: Polypropylene coated metal powder.
Output characteristics: particle size 20-50 μm , sphericity adjustable.

4.3 Post-processing

Screening: Use vibrating screen or air flow classification to control the particle size range (such as 15-45 μm).
Drying: Dry at 105±2°C for 1 hour to remove moisture.
Surface treatment: Protect with inert gas (such as Ar) to reduce oxidation.

5. Quality Control

5.1 Chemical composition

Determined according to GB/T 13305, oxygen content ≤0.2 wt %, nitrogen content ≤0.05 wt %, total impurity content ≤0.3 wt %.

5.2 Particle size distribution

Determined according to GB/T 19077.1-2008, D10 ≥10 μm , D50 = 20-50 μm , D90 ≤100 μm .

5.3 Morphology and sphericity

Observation by scanning electron microscope (SEM) showed that the sphericity was ≥0.9.

5.4 Liquidity

Measured according to GB/T 1482-2010, the outflow time is ≤35 s/50 g.

5.5 Bulk density

cm^3 (depending on the material) as measured by ASTM B214-16 .

6. Results Expression

The properties of the prepared powders are listed in tabular form:
Chemical composition: content of each element (wt %).
Particle size distribution: D10, D50, D90 (μm).

Morphology: Sphericity and SEM image description.
Flowability: Flow time (s/50 g).
Bulk density: g/ cm^3 .
The test report should include:
a) Standard number: GB/T 34505-2017;
b) Powder type: material brand, batch;
c) Preparation method: process parameters;
d) Test results: performance parameter table;
e) Test date: such as May 21, 2025;
f) Tester: signature.

7 Precision and bias

7.1 Precision

Particle size distribution: Repeatability deviation <±5 μm .
Fluidity: Repeatability deviation <±2 s.
Chemical composition: Repeatability deviation <±0.1 wt %.

7.2 Bias

Instrument error: Particle size analyzer deviation is ±2 μm , affecting particle size <±5%.
Process deviation: Gas pressure fluctuation of ±0.5 MPa causes particle size distribution to change by ±10 μm .
Environmental influence: Humidity >60% reduces fluidity by 2-5 s.

8 Influencing factors

8.1 Raw material purity

Oxygen content > 0.2 wt % increases powder surface oxidation and fluidity decreases by 5-10 s.

8.2 Process parameters

Cooling rates <10^3 K/s resulted in irregular particles with a sphericity <0.8.
Electrode speed <10000 rpm results in larger particle size (>200 μm).

8.3 Post-processing

Uneven sieving results in a particle size distribution deviation of >10%.
Insufficient drying reduces the bulk density by 0.1-0.2 g/ cm^3 .

9 Application of preparation results

9.1 Additive Manufacturing Process

Particle size 15-45 μm , fluidity <35 s/50 g, suitable for SLM printing.

9.2 Performance Optimization

Sphericity>0.9, oxygen content<0.1 wt % Improve the tensile strength of printed parts (>800 MPa).

9.3 Examples

Ti-6Al-4V powder (D50 = 35 μm , fluidity 32 s/50 g) is used for aviation turbine blades with a surface roughness of Ra <10 μm .

10. Notes

10.1 Instrument Calibration

The particle size analyzer and Hall flow meter were calibrated before testing, with a deviation of <±1%.

10.2 Process Control

Ensure gas purity >99.99% to avoid contamination.

10.3 Environmental Control

The test room temperature was 23±2°C and the humidity was 50±5%.

10.4 Security Protection

Wear protective glasses during operation to prevent metal powder from flying.

11 Appendix (Informative Appendix)

Appendix A Typical Metal Powder Preparation Parameters

Table A.1 Process parameters of different preparation methods

method	Material	Temperature (°C)	Pressure(MPa)	Particle size (μm)	Sphericity	Oxygen content (wt %)
Gas atomization	Ti-6Al-4V	1700	3.0	20-50	>0.9	<0.15
PREP method	Tungsten Alloy	1800	4.0	30-100	>0.95	<0.10
Mechanical alloying	Aluminum-based composite materials	Room temperature	-	1-50	<0.7	<0.20

Appendix B Error Analysis

B.1 Instrument error

The particle size analyzer has a deviation of ±2 μm , affecting the particle size by <±5%.

B.2 Process Deviation

A gas pressure fluctuation of ±0.5 MPa causes the particle size distribution to vary by ±10 μm .

B.3 Environmental Impact

Humidity >60% reduces fluidity for 2-5 s.

Appendix C Improvement Suggestions

C.1 Laser particle size analysis was used to improve the accuracy to ±1 μm .

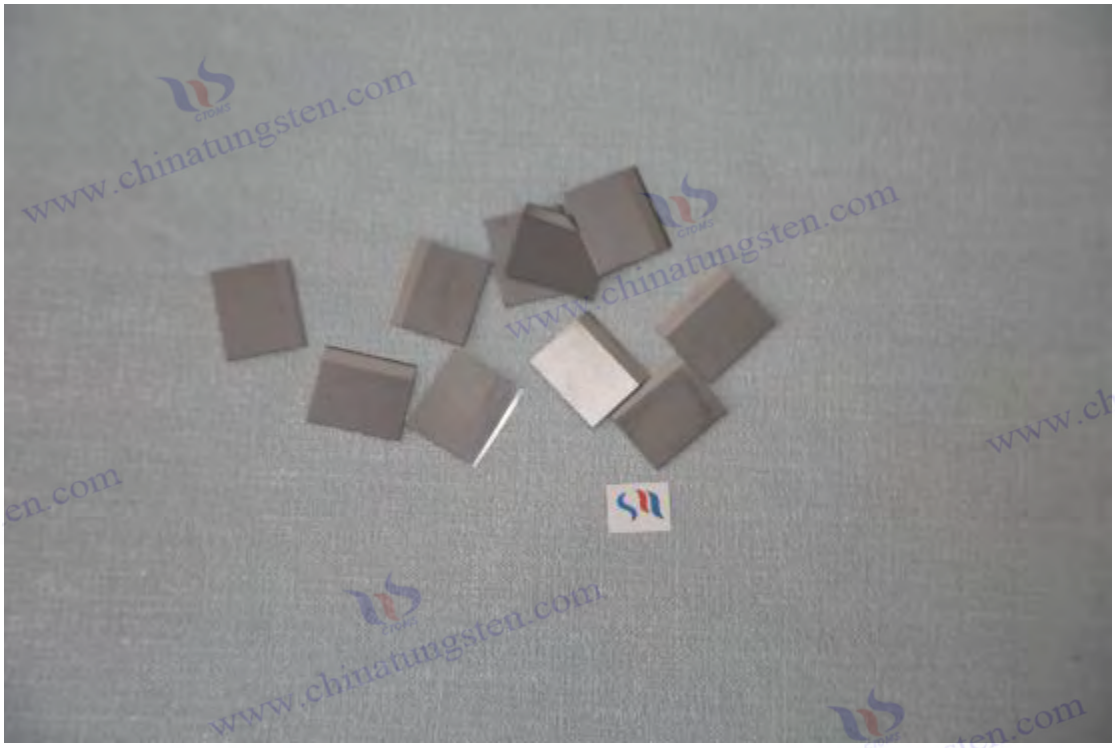
C.2 A vacuum environment was used to reduce the oxygen content to <0.05 wt %.

C.3 An online monitoring system was introduced to optimize process parameters.

Appendix D Test Data Examples

Table D.1 Ti-6Al-4V powder preparation test data

parameter	Measurement 1	Measurement 2	Measurement 3	average value
D50 (μm)	34.5	35.0	34.8	34.8
Flowability (s/50 g)	32.2	32.0	32.3	32.2
Oxygen content (wt %)	0.12	0.13	0.11	0.12



GB/T 26048-2010 Specification for sintering process of cemented carbide

1 Scope

This standard specifies the specifications for cemented carbide sintering process, including raw material preparation, sintering process parameters, equipment requirements, quality control and performance test methods. This method is applicable to the sintering process of cemented carbide (such as YG, YT, YW series grades) with tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase, mainly used for the production of cutting tools, molds and wear-resistant parts. This standard can be used for guidance of the sintering process, production acceptance and performance verification.

This standard does not apply to the sintering of non-Cobalt-based cemented carbides or non-WC-based cemented carbides.

2 Normative references

The following documents are essential for the application of this standard. For any dated referenced document, only the dated version applies to this standard. For any undated referenced document, the latest version (including all amendments) applies to this standard.

GB/T 18376-2014 Cemented carbide microstructure test method

GB/T 3850-2015 Method for determination of density of cemented carbide

GB/T 5169-2013 Test method for porosity of cemented carbide

GB/T 5243-2008 Method for marking properties of cemented carbide grades

ISO 3327 Method for determination of flexural strength of cemented carbide

ISO 4499-2 Methods for determination of mechanical properties of cemented carbide Part 2:

Hardness

3 Terms and definitions

The following terms and definitions apply to this standard.

3.1 Hardmetal is a composite material made of tungsten carbide (WC **)**
as the hard phase and cobalt (Co) as the bonding phase through powder metallurgy.

3.2 Sintering is

the process of combining powder particles into a dense solid by heating, usually at a temperature below the melting point of the main components.

3.3 Liquid-Phase Sintering

During the sintering process, the binding phase (such as cobalt) melts to form a liquid phase, which promotes particle rearrangement and densification.

3.4 Solid-State Sintering:

During the sintering process, no liquid phase is formed , and the particle bonding is achieved only through solid-state diffusion.

3.5 Microstructure

The organizational characteristics of cemented carbide after sintering, including grain size, porosity and phase distribution.

4 Sintering process

4.1 Raw material preparation

Powder selection: Use high purity WC and Co powders, WC purity ≥ 99.8%, Co purity ≥ 99.9%, impurity content ≤ 0.1 wt %.

Particle size: WC grain size 0.5-2.0 μm , Co powder particle size 1-3 μm .

Mixing: Dry or wet ball milling is used for mixing, with a ball-to-material ratio of 5:1 to 10:1 for 24-48 hours to ensure uniformity (deviation <±0.5 wt %).

Pressing: Press the mixed material into a green body at a pressure of 100-300 MPa and a green body density of 50%-60% of the theoretical density.

4.2 Sintering process

4.2.1 Single-stage sintering (vacuum sintering)

Equipment: Vacuum sintering furnace, maximum temperature 1550°C, vacuum degree ≤10^{-2} Pa .

Process parameters:

Heating rate: 5-10°C/min to 600°C (additive removal), hold for 1 hour.

Continue to raise the temperature to 1400-1450°C (liquid phase sintering temperature) and keep it

at this temperature for 1-2 hours.
Cooling rate: 5-10°C/min to 1000°C, then cool naturally to room temperature.
Atmosphere: vacuum or low-pressure argon (<0.1 MPa).
Applicable grades: YG6, YG8, suitable for cutting tools.

4.2.2 Two-stage sintering (solid phase + liquid phase sintering)
Equipment: hydrogen atmosphere sintering furnace, vacuum sintering furnace.
Process parameters:
Solid phase sintering: Keep at 1300-1350°C (below the melting point of cobalt) for 1 hour in a hydrogen atmosphere to promote initial bonding of particles.
Liquid phase sintering: Raise the temperature to 1450-1480°C and keep it at this temperature for 30-60 minutes in a vacuum or argon atmosphere to achieve complete densification.
Cooling: 5-10°C/min to 1000°C, then natural cooling.
Applicable grades: YT15, YW1, suitable for materials requiring fine grains.

4.2.3 Hot Isostatic Pressing (HIP Sintering)
Equipment: Hot isostatic pressing furnace, maximum pressure 100 MPa, maximum temperature 1500°C.
Process parameters:
Sintering temperature: 1400-1450°C.
Pressure: 50-100 MPa.
Keep warm time: 1-2 hours.
Cooling: Cool to room temperature in the furnace.
Applicable grades: High-performance grades (such as YG6F) are used for parts requiring low porosity.

4.3 Post-sintering treatment
Cooling: Control the cooling rate to avoid cracks caused by thermal stress.
Surface cleaning: Remove the surface oxide layer or residue and clean with ethanol.
Size adjustment: Size calibration is performed based on shrinkage (15%-20%).

5. Quality Control

5.1 Chemical composition
Determined according to GB/T 5243-2008, the deviation of WC and Co content is <±0.5 wt %, and the impurity content is ≤0.1 wt %.

5.2 Microstructure
Grain size: measured according to GB/T 18376-2014, WC grain size 0.8-1.5 μm .
Porosity: Measured according to GB/T 5169-2013, porosity ≤ 0.05%.
Phase distribution: The cobalt phase is evenly distributed without obvious segregation.

5.3 Physical properties

Density: Determined according to GB/T 3850-2015, relative density ≥99%.

Shrinkage: Linear shrinkage 15%-20%, deviation <±1%.

5.4 Mechanical properties

Hardness: measured according to ISO 4499-2, HRA ≥90.

Flexural strength: measured according to ISO 3327, ≥2000 MPa.

6 Results Expression

The properties after sintering are listed in table form:

Chemical composition: WC, Co content (wt %).

Microstructure: grain size (μm), porosity (%).

Physical properties: density (g/cm³) , shrinkage (%).

Mechanical properties: hardness (HRA), flexural strength (MPa).

The test report should include:

a) Standard number: GB/T 26048-2010;

b) Brand: such as YG6;

c) Sintering process: single stage, two stages or HIP;

d) Process parameters: temperature, time, atmosphere;

e) Test results: performance parameter table;

f) Test date: such as May 21, 2025;

g) Tester: signature.

7 Precision and bias

7.1 Precision

Grain size: Repeatability deviation <±0.1 μm .

Porosity: Repeatability deviation <±0.02%.

Hardness: Repeatability deviation <±0.5 HRA.

Bending strength: Repeatability deviation <±50 MPa.

7.2 Bias

Instrument error: microscope error ±0.1 μm , affecting grain size <±5%.

Process deviation: Temperature fluctuation of ±10°C causes porosity variation of ±0.03%.

Environmental influence: Oxygen content in the atmosphere >0.01% increases the porosity by 0.01-0.02%.

8 Influencing factors

8.1 Temperature

Temperatures <1400°C result in insufficient densification and porosity >0.1%; temperatures >1480°C cause abnormal grain growth (>2 μm).

8.2 Holding time

When the holding time is <30 minutes, the densification is incomplete and the relative density is <98%. When the holding time is >2 hours, the grains grow and the hardness decreases by 0.5-1 HRA.

8.3 Atmosphere

Oxygen content > 0.01% leads to surface oxidation and an increase in porosity of 0.02-0.05%.

8.4 Powder properties

Grain size <0.5 μm increases hardness (>92 HRA) but decreases flexural strength (<1800 MPa).

9 Application of sintering results

9.1 Cutting tools

YG6 (hardness 91.5 HRA, bending strength 2200 MPa), used for turning tools, life > 5 hours.

9.2 Process Optimization

Porosity > 0.05% indicates that the sintering temperature is insufficient and should be adjusted to 1450°C.

9.3 Performance Prediction

Relative density>99%, hardness>91 HRA corresponding to a 20% increase in wear resistance.

9.4 Examples

YG8 (two-stage sintering, grain size 1.0 μm , flexural strength 2400 MPa), used for stamping dies, life span >10,000 times.

10. Notes

10.1 Instrument Calibration

The sintering furnace temperature and vacuum degree were calibrated before testing, with a deviation of <±1%.

10.2 Process Control

Ensure that the atmosphere purity is >99.99% and avoid oxidation.

10.3 Environmental Control

The sintering chamber temperature was 23±2°C and the humidity was <60%.

10.4 Security Protection

Wear protective glasses during operation to prevent powder from flying.

11 Appendix (Informative Appendix)

Appendix A Typical sintering process parameters

Table A.1 Sintering parameters of different grades

Brand	Sintering method	Temperature (°C)	Holding time (min)	atmosphere	Relative density(%)	Grain size (μm)
YG6	Vacuum sintering	1450	60	vacuum	99.5	0.8-1.0
YG8	Two-stage sintering	1350+1480	60+30	Hydrogen + vacuum	99.3	1.0-1.2
YT15	HIP sintering	1450	90	Argon + pressure	99.8	0.6-0.8

Appendix B Error Analysis

B.1 Instrument error

Temperature deviation of ±10°C affects porosity by <±0.03%.

B.2 Process Deviation

A holding time deviation of ±5 minutes results in a relative density change of ±0.5%.

B.3 Environmental Impact

Atmospheric oxygen content > 0.01% increases the porosity by 0.01-0.02%.

Appendix C Improvement Suggestions

C.1 Use online temperature monitoring to control the deviation <±5°C.

C.2 Use high-purity inert gas to reduce the oxygen content to <0.005%.

C.3 Introduce rapid cooling technology to reduce grain growth.

Appendix D Test Data Examples

Table D.1 YG6 sintering test data

parameter	Measurement 1	Measurement 2	Measurement 3	average value
Relative density(%)	99.4	99.5	99.6	99.5
Grain size (μm)	0.9	0.8	1.0	0.9
Hardness (HRA)	91.4	91.6	91.5	91.5

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