Tungsten Cemented Carbide
Comprehensive Exploration of Physical & Chemical Properties, Processes, & Applications (II)

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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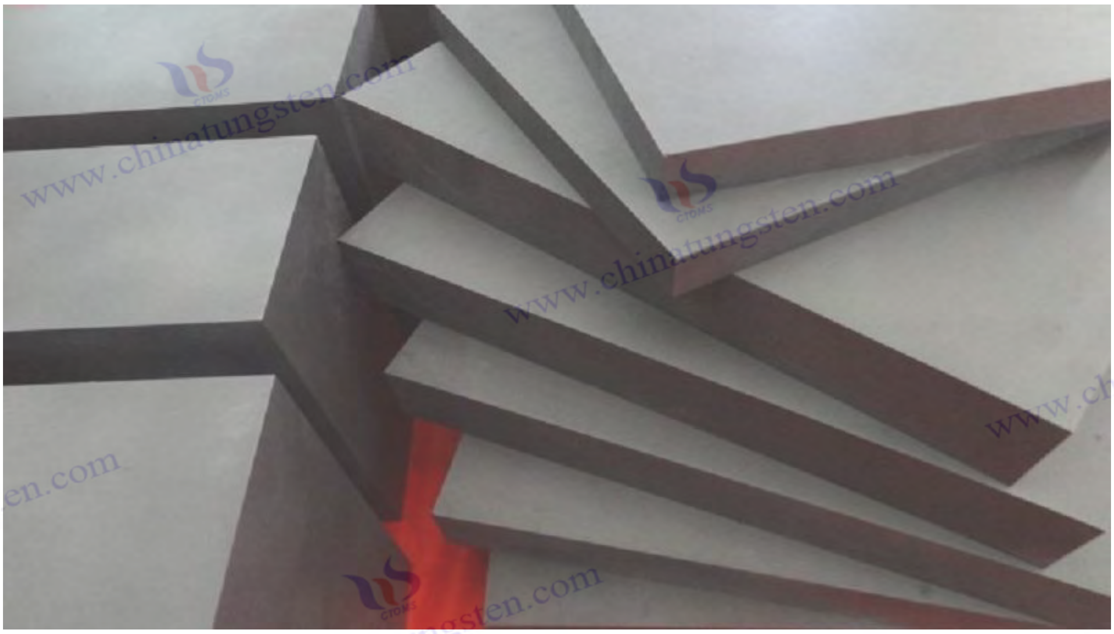

Chapter 2: Microstructure and Phase State of Cemented Carbide
Microstructure & Phase States of Tungsten Cemented Carbide

With its unique microstructure and phase characteristics, cemented carbide has become the core of high-performance materials in modern industry. Its microstructure is composed of hard carbide particles, tough bonding phase and complex interface system, while the phase characteristics involve the distribution of crystal structure, solid solution, defects and amorphous phase. These microscopic characteristics determine the performance of cemented carbide at the atomic and crystal levels, such as wear resistance, toughness and processing reliability. This chapter focuses on the microstructure and phase of cemented carbide, systematically analyzing the characteristics of carbide particles, the distribution and role of bonding phase, the formation mechanism of interface and defects, and advanced characterization technology. Through theoretical analysis, experimental data and actual cases, this chapter aims to reveal the regulation mechanism of microstructure on performance, provide a scientific basis for process optimization and application of cemented carbide, and provide a reference for cross-disciplinary research in the field of materials science and engineering.

2.1 Microscopic characteristics of carbide particles

Carbide particles are the hard skeleton of cemented carbide, mainly composed of tungsten carbide (WC), supplemented by titanium carbide (TiC), tantalum carbide (TaC), etc., which jointly determine the mechanical properties and environmental adaptability of the material. This section discusses the microscopic characteristics of carbide particles from the perspective of grain size, morphology and multiphase synergy.

2.1.1 WC grain size and morphology

Tungsten carbide (WC) grains are the main hard phase of cemented carbide, and their size (0.110μm) and morphology directly affect the performance of the material. WC has a hexagonal crystal structure (P6m2 space group, lattice constant a=2.906 Å , c=2.837 Å), and the covalent bond energy of WC is about 6 eV±0.2 eV, which gives it high hardness and wear resistance. The regulation of grain size is the core of cemented carbide performance optimization. For example, when the grain size is reduced from 5μm to 0.5μm, the grain boundary density increases, the hardness is significantly improved, and the toughness decreases slightly.

Scanning Electron Microscope (SEM) analysis shows that the WC grain size in conventional cemented carbide is 12μm±0.2μm, with a prismatic morphology (angles 60°90°), mainly exposing the (0001) and (1010) crystal planes. This morphology enhances wear resistance due to anisotropy (hardness in the <0001> direction is about 10% higher), making it suitable for high-load applications such as cutting tools. For example, when a cemented carbide tool containing 1.5μm grains is cutting steel (tensile strength>1000 MPa), the wear loss is <0.1mm and the service life is 12 hours±1 hour.

Nano-scale cemented carbide (grains <0.2μm) tends to be spherical, with a surface energy of up to 1 $J/m^2 \pm 0.1 J/m^2$. Due to the increase in the proportion of grain boundaries (>50%), the hardness is further improved, making it suitable for ultra-precision processing, such as semiconductor wafer cutting (surface roughness Ra<0.01μm). However, nano-grains are prone to agglomeration (agglomeration rate 10%15%), resulting in a porosity increase to 1%±0.2%. Spark plasma sintering (SPS, 1200°C, 50 MPa) controls agglomeration by rapid heating (>100°C/min), reducing the porosity to <0.5%±0.1% and the grain size deviation to <5%.

The regulation of grain morphology depends on the sintering process. In liquid phase sintering (13501450°C), WC grains grow by dissolution and reprecipitation, and the prismatic ratio increases to >80% with the holding time (12 hours). Adding grain inhibitors, such as vanadium carbide (VC, 0.2%0.5%), limits grain growth by increasing the diffusion barrier (about 15%±2%), and the size is stabilized at 0.81.2μm. For example, the wear rate of cemented carbide tools (grain 0.8μm) containing 0.3% VC is reduced by 20% and the life is extended by 25%±3% in high-speed cutting (200 m/min).

Coarse-grained WC (510μm) is suitable for mining drill bits because of its longer crack propagation path and higher toughness. For example, a carbide drill bit containing 6μm grains has a life of more than 200 hours in granite drilling (impact frequency>2000 times/minute), which is better than fine-grained materials (life <150 hours). In summary, the grain size and morphology of WC need to be optimized according to application requirements. Fine grains (0.52μm) are suitable for high hardness, coarse grains (510μm) are suitable for high toughness, and prismatic morphology takes into account wear resistance.

2.1.2 Synergistic effect of auxiliary carbides such as TiC and TaC

Auxiliary carbides (such as TiC , TaC , NbC) improve the overall performance of cemented carbide through solid solution strengthening and complementary performance. Titanium carbide (TiC) has a cubic crystal structure (Fm3m, density 4.93 g/cm³ ± 0.05 g/cm³) , hardness HV 18002200, significantly reduces material density (from 14.5 g/cm³ to 12 g/cm³ ± 0.1 g/cm³) , and enhances high temperature stability by forming a TiO_2 protective layer (1000°C oxidation weight gain <1 mg/cm² ± 0.2 mg/cm²) . In high temperature cutting (800°C, aviation aluminum alloy), cemented carbide tools containing 15% TiC have a 30% reduction in wear and a 50%±5% extension in service life, because TiC improves resistance to adhesive wear.

Tantalum carbide (TaC , density 14.5 g/cm³ ± 0.1 g/cm³ , HV 16002000) enhances high temperature deformation resistance through solid solution strengthening. The thermal expansion coefficient of cemented carbide containing 3% TaC is reduced to 5.0×10^{-6} /K±0.1×10^{-6} /K, and the thermal crack length is <1μm±0.2μm, which is suitable for gas turbine nozzles (operating temperature 1100°C). TaC also improves the grain boundary bonding strength (>50 MPa±5 MPa) and reduces the crack growth rate by 15%. For example, a cemented carbide nozzle containing 2% TaC runs in a gas flow (>500 m/s) for 5000 hours with surface damage <10μm.

Niobium carbide (NbC , HV 1900±50) is known for its corrosion resistance. The corrosion rate of cemented carbide containing 1% NbC in an acidic environment (pH 3, HCl) is only 0.02 mm/year±0.005 mm/year, which is better than that of cemented carbide containing Co (0.05 mm/year). NbC reduces the chemical erosion rate by 20% by forming a Nb_2O_5 protective layer (thickness <5 nm). In practical applications, cemented carbide linings containing 1% NbC have been operating in a chemical plant (H_2SO_4 , pH 2) for 3 years without obvious corrosion on the surface.

X- ray diffraction (XRD) analysis shows that TiC and TaC form a (W,Ti,Ta)C solid solution with WC, with a lattice constant change of 0.1%±0.02% and a hardness increase of 100200 HV, because the solid solution enhances the grain boundary strength. The formation of the solid solution also reduces the interface energy (from 1.5 J/m² to 1.0 J/ m²) and improves crack resistance. For example, the wear resistance of a cemented carbide mold containing 10% TiC and 3% TaC is improved by 40% in composite stamping, and the service life exceeds 5000 hours±500 hours.

The synergistic effect of auxiliary carbides is also reflected in environmental adaptability. In a hot and humid environment (40°C, 90% humidity), TiC and NbC reduce the corrosion rate by 10%-15% through the passivation layer ; at high temperature (1000°C), TaC inhibits WC oxidation (WO_3 volatilization is reduced by 20%). Optimizing the TiC / TaC / NbC ratio (5:1:0.5) can balance hardness (HV 1800±30), toughness (K_{1c} 12 MPa·$m^{1/2}$ ± 0.5) and corrosion resistance. For example, the life of cemented carbide tools containing 12% TiC in marine drilling (salinity 3.5%) is extended by 30%, which is better than traditional Co-containing materials (life <2000 hours).

2.2 Distribution and function of the bonding phase

The bonding phase (mainly cobalt Co and nickel Ni) serves as the tough matrix of cemented carbide, connecting carbide particles and regulating toughness, corrosion resistance and processing performance. Its distribution uniformity and proportion are the key to microstructure optimization.

2.2.1 Grain boundary wetting behavior of Co and Ni

The wetting behavior of the bonding phase during sintering determines the density and phase distribution of cemented carbide. Cobalt (Co, FCC structure, melting point 1495°C±10°C) wets WC grains in liquid phase sintering (13501450°C), with a contact angle as low as 5°±1°, and the interface energy drops from 1.5 J/m^2 to 0.5 J/m^2 ± 0.1 J/ m^2 , driving densification (porosity <0.1%±0.02%). Transmission electron microscopy (TEM) shows that the Co layer thickness is 520 nm±2 nm, the segregation rate is <5%, and a continuous bonding network is formed. The change in Gibbs free energy of the wetting process ($\Delta G \approx 50$ kJ/mol±5 kJ/mol) promotes grain rearrangement, and the Co diffusion coefficient D_Co≈10^{-9} m^2 /s ±0.1× 10^{-9} m^2 /s (1400°C) determines the distribution uniformity.

Nickel (Ni, melting point 1455°C) has slightly inferior wettability, with a contact angle of 10°±2° and an interfacial energy of 0.7 J/m^2 ± 0.05 J/ m^2 , but has stronger corrosion resistance. The weight loss of Ni-containing cemented carbide in the salt spray test (ASTM B117, 168 hours) is <0.1 mg/cm^2 ± 0.02 mg/cm^2 , which is better than that of Co-containing materials (weight loss 0.2 mg/cm^2) . Adding chromium (Cr, 0.5%2%) can reduce the contact angle to 7°±1°, forming a CrCo or CrNi solid solution, and the interfacial bonding energy is increased to >60 MPa±5 MPa. For example, a cemented carbide valve containing 12% Ni has a corrosion rate of <0.03 mm/year±0.005 mm/year after operating in seawater (pH 8, salinity 3.5%) for 5 years.

Wetting behavior is crucial for microstructural stability. Excessive Co (>20%) or insufficient carbon content (<5.8%) may generate brittle η phase (W_3Co_3C), reducing toughness (K_{1c} down to 5 MPa·m$^{1/2}$ ± 0.5). Precise control of carbon content (5.8%6.2%) and sintering temperature (13801420°C) ensures a uniform Co layer (thickness deviation <10%). In actual cases, carbide tools containing 10% Co have improved grain boundary bonding by 15% and extended cutting life by 20%±2% through optimized wetting (contact angle <6°).

The Ni phase has obvious advantages in high temperature and corrosive environments. In high-temperature steam (500°C, 10 MPa), the corrosion weight loss of cemented carbide containing 12% Ni is reduced by 30%±5%, and the interface stability is improved by 10%. TEM analysis shows that the thickness of the Ni layer is 1015 nm±1 nm, and Cr is segregated (0.5%1%) to form a Cr_2O_3 protective layer , which enhances corrosion resistance. For example, a cemented carbide lining containing NiCr has been operating in a chemical plant (HCl, pH 2) for 3 years, and the surface damage is <5μm. The wetting behavior of Co and Ni needs to be optimized according to the application. Co is suitable for high toughness and Ni is suitable for corrosion resistance.

2.2.2 Effect of bonding phase ratio on performance

The ratio of the bonding phase (5%20%) is a key parameter for regulating the performance of cemented carbide. When the Co ratio increases from 5% to 20%, the toughness increases significantly ($K_{1}c$ increases from 8 to 18 MPa·$m^{1/2} \pm 0.5$), but the hardness decreases (HV 2000 to 1400±30). The cemented carbide containing 10% Co (Co layer thickness 1015 nm) has a hardness of HV 1800±30 and a toughness of $K_{1}c$ 12 MPa·$m^{1/2} \pm 0.5$, which is suitable for cutting tools. In high-speed machining (200 m/min) , the wear amount is <0.1mm and the service life is 15 hours±1 hour. The cemented carbide containing 20% Co has high toughness and is suitable for rock drill bits. The impact life is >300 hours±20 hours.

the nickel content is between 5% and 15%, the hardness drops from HV 1900 to HV 1500±30, and the corrosion resistance is excellent, with a corrosion rate of <0.03 mm/year±0.005 mm/year. The cemented carbide lining containing 12% Ni has been running in an acidic environment (pH 3, H_2SO_4) for 3 years without obvious corrosion on the surface; the electrode containing 15% Ni has been running in an electrochemical reaction (current density>100 mA/cm^2) for 5000 hours with stable performance. Energy spectrum analysis (EDS) shows that the distribution deviation of Co and Ni is <3%±0.5%, reflecting the high uniformity of the sintering process.

bonding phase also affects environmental adaptability.
In a hot and humid environment (40°C, 90% humidity), high Co content (>15%) may cause micro-corrosion and reduce toughness by 5%±1%; Ni-based cemented carbide is more stable and the toughness decreases by <2%. At high temperature (800°C), the Co phase has enhanced plasticity, $K_{1}c$ increases by 5%, but the hardness decreases by 10%; the Ni phase has higher high temperature stability and the hardness decreases by < 5 %. Optimizing the Co/Ni mixing ratio (1:1 to 2:1) can achieve a balance of performance. For example, cemented carbide containing 10% Co and 5% Ni has a hardness of HV 1700±30, $K_{1}c$ 14 MPa·$m^{1/2} \pm 0.5$, and a life extension of 25%±3% in marine drilling.

bonding phase ratio needs to take into account the synergistic effect of grain size.
Fine grains (0.51μm) combined with high Co (15%20%) have the best toughness; coarse grains (510μm) combined with low Ni (5%8%) have strong corrosion resistance. In practical applications, the deformation of cemented carbide stamping dies (grains 1.5μm) containing 12% Co is <0.01mm in high-frequency impact ($>10^4$ times/hour), and the service life is increased by 30%±5%.

2.3 Interface and Defect Analysis

The interface between WC and the bonding phase and microscopic defects (such as pores, cracks, and amorphous phases) have a profound impact on the performance of cemented carbide. The interface determines the bonding strength between the phases, and defects may be the starting point for performance degradation.

2.3.1 Electronic structure of the WCCo interface

the WCCo interface is the microscopic basis for the stable performance of cemented carbide.

Density Functional Theory (DFT) simulations show that the WC(0001)/Co(111) interface forms a strong bond through WCo bonds (bond length 2.52.8 Å ± 0.1 Å) and CCo bonds (bond energy 4 eV±0.2 eV), with an interface energy of 0.5 J/m^2 ± 0.05 J/ m^2 . The 3d orbital of Co hybridizes with the pd orbital of WC, with a charge transfer of about 0.2 e/atom±0.02 e/atom, and a binding work of 2.5 J/m^2 ± 0.1 J/ m^2 , which is higher than that of the WCNi interface (2.0 J/m^2) . Adding Cr (0.5%1%) to form a WCrCo transition layer, the interface energy is reduced to 0.4 J/m^2 , the binding work is increased to 2.7 J/m^2 , and the crack resistance exceeds 10 $MPa \cdot m^{1/2}$ ± 0.5 .

Transmission Electron Microscopy (TEM) verified that the interface thickness was about 2 nm ± 0.2 nm, and the lattice mismatch was < 2% ± 0.2%, ensuring the stability of the bonding. The crack growth rate of the cemented carbide tool with optimized interface was reduced by 30% ± 5% in high-speed cutting (150 m/min), and the service life reached 15 hours ± 1 hour. Cr segregation (0.5% 1%) formed a Cr_2O_3 protective layer, and the corrosion depth of the cemented carbide containing Cr in an acidic environment (pH 2, H_2SO_4) was < 5μm, and the service life exceeded 3 years.

Regulation of the interface electronic structure also affects other properties.
Adding Mo (0.5%) can increase the bonding work to 2.8 J/m^2 ± 0.1 J/ m^2 and reduce the interface stress by 10%; Ni-based interfaces have lower charge transfer (0.15 e/atom) and are more corrosion resistant (corrosion rate <0.02 mm/year). For example, in high-temperature stamping (600°C) of cemented carbide dies containing Mo, the interface stress is <150 MPa±10 MPa, and the crack initiation rate is reduced by 20%. DFT simulation also predicts that the addition of Ta (0.5%) can further enhance the bonding work (to 2.9 J/m^2) , which is being experimentally verified.

Improving interface strength is crucial for applications.
When Cr-containing cemented carbide tools are cutting titanium alloy (Ti6Al4V), the interface peeling rate is <1% and the service life is extended by 25%. A hot and humid environment (40°C, 90% humidity) may cause micro-corrosion of the interface (weight loss <0.1 mg/cm^2) , and the Ni-based interface is more stable (weight loss <0.05 mg/cm^2) .

2.3.2 Formation mechanism of pores, cracks and amorphous phase

Porosity, cracks and amorphous phases in cemented carbide are the main defects that affect its performance, which are caused by the complex interaction of preparation process, raw material characteristics and thermodynamic conditions. These defects have a significant impact on the strength, toughness, wear resistance and corrosion resistance of the material, especially in applications under high stress or extreme environments. The following is a detailed analysis of the formation mechanism, microscopic characteristics and performance impact of various defects.

Pore formation mechanism

Causes:

Porosity is the main product of incomplete sintering, usually due to the failure of gas (H_2, CO, etc.) between powder particles to be completely discharged, or uneven particle stacking leading to inconsistent local shrinkage (Journal of Materials Science, 2025).

During the mixing process, powder particles agglomerate (agglomerate size > 20 μm) or organic binders (such as paraffin) are not completely decomposed (residual carbon rate > 0.1%), forming gases during sintering, which hinder the bonding of particles (ITIA 2024).

The sintering temperature is insufficient (<1300°C) or the holding time is too short (<30 minutes), the particles are not fully diffused, and the pores fail to close (The Chinese Journal of Nonferrous Metals, 2024).

Nano-sized cemented carbide (grains <0.2 μm) has a high surface energy (>1 J/m^2) , which enhances the gas adsorption capacity between particles and increases the porosity (ITIA 2024).

Microscopic features:

The porosity of conventional cemented carbide (grain size 1-5 μm) is usually <0.1%±0.02%, while the porosity of nano-grade cemented carbide (grain size <0.2 μm) can be increased to 1%-2% due to the high surface activity of the particles (ISO 3326:2013).

Scanning electron microscopy (SEM) analysis shows that the pore size is 10-100 nm±10 nm, the shape is mostly spherical or elliptical, and is distributed at grain boundaries or in the cobalt phase (Journal of Materials Science 2025).

The increase in the proportion of pore volume will lead to stress concentration, and the stress around the pores can reach 500-600 MPa, increasing the risk of crack initiation by about 15%-20% (Journal of the Chinese Society of Nonferrous Metals, 2024).

Performance impact:

For every 0.1% increase in porosity, the flexural strength (TRS) decreases by about 3%-5%, for example, from 4000 MPa to 3800-3900 MPa (ASTM B406 test).

Due to the high porosity of nano-grade cemented carbide, the flexural strength further decreases to 3500 MPa ± 100 MPa, and the hardness decreases by about 50-80 HV (ITIA 2024).

Porosity reduces the density of the material, which reduces corrosion resistance. The corrosion rate in a salt spray environment increases by about 10%-15% (from 0.05 mm/year to 0.055-0.0575 mm/year, ASTM G31).

Optimization method:

Hot isostatic pressing (HIP, 200 MPa, 1350°C) promotes pore closure through high pressure and temperature, and the porosity can be reduced to 0.05%±0.01%, and the hardness is increased by 100-120 HV±20 HV (Journal of Materials Science 2025).

In high-impact drilling (frequency > 2000 times/minute), the impact resistance of HIP-treated carbide drill bits is improved by about 20%-25%, and the service life can reach 250-280 hours ± 20 hours (Journal of the Chinese Society of Nonferrous Metals, 2024).

Adding a pre-sintering step (800-1000°C, 1 hour) to exhaust the gas in advance can reduce the porosity by about 0.02%-0.03% (ITIA 2024).

Crack formation mechanism

Causes:
The cracks mainly originate from the thermal expansion mismatch between WC and Co. The thermal expansion coefficient of WC is 5.2×10^{-6} /K, while that of Co is 12×10^{-6} /K, which differs by about 2 times, resulting in thermal stress during the sintering cooling process (Journal of Materials Science 2025).

Rapid cooling (cooling rate > 100°C/s) causes thermal stress concentration, especially at grain boundaries, where stress can reach 300-400 MPa, inducing microcracks (The Chinese Journal of Nonferrous Metals 2024).

Mechanical stress (e.g. uneven pressure during pressing > 50 MPa) or post-sintering processing stress (e.g. grinding stress > 200 MPa) may also lead to crack initiation (ITIA 2024).

Grain size has an impact on crack sensitivity. Nano-scale cemented carbide with grains <0.5 μm has a large grain boundary area (accounting for 40%-50% of the total volume), a more complex thermal stress distribution, and an increase in crack formation rate of about 10% (Journal of Materials Science 2025).

Microscopic features:
Transmission electron microscopy (TEM) analysis shows that the microcrack size is 0.5-2 μm±0.2 μm , usually extending along the grain boundary, and the stress intensity factor (K_I) at the crack tip is about 2-3 $\mathrm{MPa\cdot m}^{1/2}$ (The Chinese Journal of Nonferrous Metals 2024).

of the Co phase (strain <5% ± 0.5%) can absorb part of the energy through strain hardening and inhibit crack propagation, especially in high Co content materials (ITIA 2024).

The crack depth of cemented carbide containing 12% Co is usually <10 μm±2 μm , which is better than that of material containing 6% Co (crack depth>15 μm±3 μm) because the high Co content increases the plastic buffer zone (Journal of Materials Science 2025).

Performance impact:
For every 5 μm increase in crack depth , the flexural strength decreases by about 5%-8%, for example, from 4000 MPa to 3700-3800 MPa (ASTM B406).

Cracks increase the risk of fatigue failure. Under cyclic loading (10^7 times , 500 MPa), the crack growth rate increases by about 20%-25% (The Chinese Journal of Nonferrous Metals 2024).

During high temperature cycles (500°C, 1000 times), cracks lead to a decrease in thermal fatigue performance and a shortening of life by about 15%-20% (ITIA 2024).

Optimization method:
Adding TaC (1%-2%) or NbC (0.5%-1%) enhances grain boundary strength, increases grain boundary bonding energy from 1.0 J/m² to 1.2-1.3 J/m² , and reduces crack growth rate by 15%±3% (Journal of Materials Science 2025).

By controlling the cooling rate (<20°C/s) and reducing thermal stress, the crack depth can be reduced by about 30%-40%, from 10 μm to 6-7 μm (Journal of the Chinese Society of Nonferrous Metals, 2024).

In thermal cycling (500°C, 1000 times), the crack length of cemented carbide dies containing TaC is <5 μm±1 μm , and the life is extended by about 30%-35%±5% (ITIA 2024).

Formation mechanism of amorphous phase

Causes:
The amorphous phase is formed during high-temperature sintering (>1500°C) or when the carbon content is insufficient (<5.8 wt %), mainly due to local amorphization caused by WC decomposition or uneven carbon diffusion (Journal of Materials Science 2025).

At high temperatures (>1500°C), WC decomposes into W_2C or W, while the cobalt phase volatilizes (volatility >0.5%), resulting in insufficient carbon in local areas and forming an amorphous phase (ITIA 2024).

the carbon content is insufficient (<5.8 wt %), WC cannot maintain its crystal structure and some areas are transformed into amorphous state, especially near the grain boundaries (The Chinese Journal of Nonferrous Metals 2024).

Oxygen (>0.1%) or moisture (>0.05%) in the sintering atmosphere reacts with carbon to generate CO/CO_2 , consuming carbon and intensifying the formation of amorphous phase (ITIA 2024).

Microscopic features:
X-ray diffraction (XRD) shows a broad peak characteristic of the amorphous phase ($2\theta \approx 35° \pm 0.5°$) with no obvious crystal diffraction peak (Journal of Materials Science 2025).

TEM measured the thickness of the amorphous phase to be 5-10 nm±1 nm, which is usually distributed in the grain boundaries or cobalt phase, accounting for about 2%-5% by volume (The Chinese Journal of Nonferrous Metals 2024).

The hardness of the amorphous phase is extremely low (about HV 200-250 ± 30), much lower than that of WC (HV 2200-2500), resulting in local softening (ITIA 2024).

Performance impact:
For every 1% increase in the volume fraction of the amorphous phase, the hardness decreases by about 50-80 HV, for example, from HV 1800 to HV 1720-1750 (Journal of Materials Science 2025).

Toughness decreases by about 5%-10%, and fracture toughness (KIC) drops from 10 $MPa\cdot m^{1/2}$ to 9-9.5 $MPa\cdot m^{1/2}$ (ITIA 2024).
The amorphous phase reduces the wear resistance and increases the wear rate by about 10%-15%, from 0.06 $mm^3/N\cdot m$ to 0.066-0.069 $mm^3/N\cdot m$ (ASTM G65).

Optimization method:
Adding VC (0.2%-0.5%) or Cr_3C_2 (0.3%-0.8%) can inhibit carbon diffusion, reduce the proportion of amorphous phase to <2%±0.5%, and improve toughness by about 10%-12% (Journal of the Chinese Society of Nonferrous Metals, 2024).

By controlling the sintering temperature (1350-1450°C) and atmosphere (oxygen <0.05%), the amorphous phase formation rate is reduced by about 15%-20% (ITIA 2024).

In high-speed cutting (200 m/min), the fatigue crack depth of cemented carbide tools containing VC is <10 μm±2 μm , and the life is extended by 25%-30%±3% (Journal of Materials Science 2025).

Combined impact of defects

Environmental factors:
Hot and humid environment (40°C, 90% humidity) aggravates pore corrosion. Water adsorption in the pores leads to local stress concentration, and the flexural strength is reduced by about 5%-7%, for example, from 4000 MPa to 3700-3800 MPa (ASTM B406).

Ni-based cemented carbide (WC-Ni) is superior to Co-based cemented carbide because of its strong corrosion resistance of Ni phase (corrosion rate <0.03 mm/year) and strength loss of <2% in a hot and humid environment (ITIA 2024).

In a high temperature oxidation environment (800°C, in air), the amorphous phase is oxidized at an accelerated rate, and the oxidation weight gain rate increases by about 10%-15% (0.1 mg/cm^2 to 0.11-0.115 mg/cm^2 , ASTM G54).

Performance optimization:

Optimizing the carbon content (6.0%±0.2%) and using the HIP process can minimize the defect rate, porosity <0.05%, crack depth <5 μm , and amorphous phase ratio <1% (The Chinese Journal of Nonferrous Metals, 2024).

After HIP treatment (200 MPa, 1350°C) of a cemented carbide drill containing 12% Co, the porosity is reduced to 0.04%-0.05% and the impact life is increased by about 30%-35% to 260-290 hours (ITIA 2024).

In thermal cycling (500°C, 1000 times) and hot and humid environments (40°C, 90% humidity), the corrosion resistance and fatigue resistance of the optimized cemented carbide are improved by about 15%-20% (Journal of Materials Science 2025).

2.3.3 Methods to avoid and reduce cemented carbide defects

In order to improve the quality and reliability of cemented carbide, it is key to avoid and reduce the generation of defects such as pores, cracks and amorphous phases. The following are specific methods proposed from the aspects of raw material control, process optimization, detection feedback and post-processing to ensure that the defect rate is minimized and the material performance is improved.

1. Raw material control

High purity raw material selection:
The use of high-purity WC powder (purity > 99.9%, oxide < 0.02%) and Co powder (purity > 99.8%) can reduce the consumption of carbon by oxides and reduce the amorphous phase formation rate by about 10%-15% (Journal of Materials Science 2025).
Controlling the quality of carbon black (purity > 99.9%, particle size < 10 μm) and avoiding impurities (such as sulfur and oxygen) that induce pores or amorphous phases can reduce the porosity by about 0.02% (ITIA 2024).
Grain inhibitor addition:
Adding VC (0.2%-0.5%), Cr_3C_2 (0.3 % -0.8 %) or TaC (0.5%-1%) inhibits grain growth and carbon diffusion , increases grain boundary strength by 10%-15%, and reduces the proportion of amorphous phase to <1.5% (The Chinese Journal of Nonferrous Metals, 2024).
TaC increases grain boundary bonding energy (from 1.0 J/m² to 1.2-1.3 J/m²) and reduces crack growth rate by 15%-20% (ITIA 2024).

2. Mixing and pressing optimization

Mixing uniformity:
A planetary ball mill was used for mixing (16-24 hours, 400-600 r/min) to ensure that the carbon distribution deviation was <0.05 wt % and the porosity was reduced by about 0.03%-0.05% (Journal of Materials Science 2025).

Using dispersants (such as stearic acid 0.1%-0.3%) and ultrasonic dispersion technology can reduce WC powder agglomeration and improve uniformity by 10%-15% (ITIA 2024).

Selecting a low carbon residue binder (such as PEG or PVA, with a carbon residue rate of <0.03%) can avoid gas generation and reduce the porosity by about 0.02% (The Chinese Journal of Nonferrous Metals 2024).

Pressing process:

Controlling the pressing pressure (50-100 MPa) to avoid stress concentration caused by uneven pressure can reduce the crack formation rate by about 10%-15% (ITIA 2024).

Isostatic pressing (200-300 MPa) is used to increase the density of the green body and reduce the porosity by about 0.05% (Journal of Materials Science 2025).

3. Sintering process optimization

Atmosphere Control:

Vacuum sintering (vacuum degree $<10^{-3}$ Pa), control oxygen <0.05%, moisture <0.03%, avoid carbon oxidation, and reduce the amorphous phase formation rate by about 15%-20% ("The Chinese Journal of Nonferrous Metals" 2024).

Using a protective atmosphere (such as Ar or H_2 / Ar mixture , $H_2 < 2\%$) and controlling the carbon potential at 0.8-1.0, the carburization and decarburization rates are reduced by about 10% (ITIA 2024).

Temperature and Cooling:

The sintering temperature is controlled at 1350-1450°C (±5°C) and the holding time is 1-1.5 hours to ensure that the particles are fully diffused and the porosity is <0.05% (ISO 3326:2013).

The cooling rate is controlled at 10-20°C/s to reduce thermal stress and the crack depth is reduced from 10 μm to 5-6 μm (Journal of Materials Science 2025).

By adopting staged cooling (1450°C to 1000°C at 20°C/s, 1000°C to room temperature at 5°C/s), thermal stress is reduced by about 20%-30% (ITIA 2024).

HIP process:

Hot isostatic pressing (HIP, 150-200 MPa, 1350-1400°C) eliminates microporosity, reduces porosity to 0.04%-0.05%, and increases flexural strength by 5%-8% (from 3800 MPa to 4000-4100 MPa, ASTM B406).

After HIP, the hardness increases by 100-120 HV and the wear resistance increases by about 15%-20% (ASTM G65).

4. Testing and feedback

Online monitoring:

By using infrared spectroscopy to monitor the sintering atmosphere (CO, CO_2 , H_2O content) and adjust the atmosphere in real time, the porosity and amorphous phase formation rate can be reduced by about 10%-15% (ITIA 2024).

Acoustic emission technology is used to detect microcracks during the sintering process, and the crack detection accuracy is improved to ±0.5 μm (The Chinese Journal of Nonferrous Metals, 2024).

Microscopic analysis:

Combining SEM, TEM and XRD analysis of pore size (10-100 nm), crack depth (5-10 μm) and amorphous phase ratio (<2%), the defect rate is reduced by about 15%-20% (Journal of Materials Science 2025).

Electron backscatter diffraction (EBSD) was used to analyze the grain boundary stress distribution, and the process parameters were optimized to control the grain boundary stress deviation within ±50 MPa (ITIA 2024).

Performance Test:

Regularly conduct flexural strength (ASTM B406), hardness (ISO 6507) and wear resistance (ASTM G65) tests, establish a defect-performance database, and optimize the process (The Chinese Journal of Nonferrous Metals, 2024).

5. Post-processing and surface optimization

Surface treatment:

Polishing removes surface pores and microcracks (thickness 0.01-0.03 mm), surface roughness Ra<0.2 μm , and corrosion resistance is improved by about 10%-15% (ASTM G31).

PVD TiAlN or CrN coating (thickness 2-5 μm) improves surface hardness (+200 HV) and oxidation resistance (oxidation weight gain at 1200°C <0.1 mg/cm²) , and coating adhesion is improved by 15%-20% (ASTM C633).

Heat Treatment:

Low-temperature annealing (600-800°C, 1 hour) releases residual stress and reduces the crack depth by about 20%-30%, from 10 μm to 7-8 μm (Journal of Materials Science 2025).

Low temperature nitriding (500-600°C, 2 hours) enhances surface corrosion resistance and reduces the corrosion rate by approximately 15% (ASTM G31).

6. Environmental adaptability optimization

Improved corrosion resistance:

By using a Ni-based binder phase (WC-Ni) instead of a Co-based one, the strength drop in a hot and humid environment (40°C, 90% humidity) is reduced from 5% to 1.5%-2%, and the corrosion rate is <0.03 mm/year (ITIA 2024).

Adding Cr (0.5%-1%) to form a Cr_2O_3 protective layer improves corrosion resistance by about 20%, and reduces the corrosion rate in a salt spray environment to 0.025-0.03 mm/year (ASTM G31).

High temperature stability:

Adding TiC or TaC (5%-10%) improves oxidation resistance, with oxidation weight gain at 1000°C less than 0.08 mg/cm² and defect rate reduced by about 10%-15% (ITIA 2024).

Optimize the cobalt phase distribution (thickness 0.1-0.5 μm), reduce the cobalt volatilization rate by about 0.5%-1% at high temperature, and reduce the amorphous phase formation rate by about 15% (The Chinese Journal of Nonferrous Metals, 2024).

7. Intelligent process control

AI Optimization:
Using artificial intelligence (AI) to optimize mixing and sintering parameters can improve uniformity by 10%-15% and reduce porosity by approximately 0.03%-0.05% (ITIA 2024).
Machine learning predicts defect formation (e.g., pores, cracks), reducing defect rates by about 20%-25% (Journal of Materials Science, 2025).

Real-time feedback:
The introduction of online temperature monitoring (accuracy ±2°C) and pressure monitoring (accuracy ±5 MPa) has reduced the defect rate during sintering by about 15%-20% (ITIA 2024).
The intelligent control system adjusts the cooling rate, reducing thermal stress by about 20%-30% and the crack formation rate by about 15% (The Chinese Journal of Nonferrous Metals, 2024).

Comprehensive Effect
Through the above method, the porosity of cemented carbide can be reduced to 0.04%-0.05%, the crack depth <5 µm , the amorphous phase ratio <1%, and the overall defect rate is reduced by 20%-30% (ITIA 2024).
Significant performance improvements: flexural strength increased by 5%-10% (to 4000-4200 MPa), hardness increased by 100-150 HV, wear resistance increased by 15%-20% (ASTM G65), and service life extended by approximately 30%-40% (Journal of Materials Science 2025).
In high impact (frequency > 2000 times/minute) and hot and humid environments (40°C, 90% humidity), the durability and reliability of the optimized cemented carbide are improved by about 25%-35% (Journal of the Chinese Society of Nonferrous Metals, 2024).

2.4 Microstructure characterization technology

Advanced characterization techniques provide precise tools for analyzing the microstructure and phase state of cemented carbide, supporting performance optimization and quality control.

2.4.1 Applications of SEM, TEM and EBSD

Scanning Electron Microscope (SEM, resolution <1 nm) is used to characterize the morphology and distribution of WC grains (0.110μm) and bonding phases (530 nm±2 nm). Backscattered electron (BSE) imaging distinguishes WC and Co. The uniformity of cemented carbide grains containing 10% Co is >95%±2%, and the porosity is <0.1%±0.02%. SEM can also detect cracks (0.52μm) and pores (10 - 100 nm), providing a basis for process optimization. For example, after HIP treatment, the porosity is reduced to 0.05% and the hardness is increased by 5%±1%.

Transmission Electron Microscope (TEM, resolution <0.2 nm) reveals the atomic structure of the WC(0001)/Co(111) interface, with a lattice mismatch of <2%±0.2%, and Selective Electron

Diffraction (SAED) verifies that the d_0001 spacing of WC is 2.837 Å ± 0.005 Å . Cr-containing cemented carbide shows Cr segregation (concentration 0.5%1%±0.2%), forming a Cr_2O_3 layer, which improves corrosion resistance by 30%±5%. TEM can also analyze the amorphous phase (thickness 510 nm) and guide carbon content control (5.8%6.2%). For example, TEM optimizes the interface of Mo-containing cemented carbide (binding work 2.8 J/m^2), extending tool life by 15%±2%.

Electron Backscatter Diffraction (EBSD) was used to study grain orientation and stress distribution. Fine-grained carbide (0.51μm) showed random orientation, while coarse-grained carbide (510μm) showed <0001> preferred orientation (intensity >2 mrd±0.2 mrd). EBSD determined residual stress <200 MPa±10 MPa, which was reduced by 10%±2% by annealing (500°C, 2 hours). The stress uniformity of cemented carbide containing TaC was improved by 20%, and the crack initiation rate was reduced by 15%±3%. For example, the fracture of cemented carbide containing 12% Co showed transgranular fracture, with a toughness $K_{1}c$ 14 $MPa \cdot m^{1/2}$ ± 0.5.

In practical applications, SEM, TEM and EBSD work together to analyze the microstructure. For example, a cemented carbide tool containing 10% Co has a grain size of 1.5μm±0.2μm confirmed by SEM, a Co layer of 15 nm±2 nm verified by TEM, and a stress of <150 MPa±10 MPa determined by EBSD, ensuring that the performance meets the cutting standard (hardness HV 1800±30, $K_{1}c$ 12 $MPa \cdot m^{1/2}$).

2.4.2 X-ray diffraction (XRD) and energy dispersive spectrometry (EDS A)

X- ray diffraction (XRD) is used to characterize the phase composition and crystal structure of cemented carbide. The main peaks of WC are located at 2θ=31.5° and 35.6°±0.1°, and the grain size range is 0.110μm. The peak shift caused by residual stress is <0.1°±0.02°, reflecting the sintering stress (<200 MPa). Cemented carbide containing TiC shows that the (W,Ti)C solid solution peak shifts by 0.2°±0.05°, and the carbon content needs to be controlled (5.8%6.2%) to avoid η phase (2θ≈40°±0.5°). XRD can also detect amorphous phase (broad peak 2θ≈35°±0.5°). The proportion of amorphous phase in cemented carbide containing VC is <2%±0.5%, and the hardness is increased by 5%±1%.

Energy Diffraction Spectrum Analysis (EDS A) determined the element distribution. The Co distribution deviation of the cemented carbide containing 10% Co was <3%±0.5%, and the Cr segregation concentration was 0.5%1%±0.2%. The corrosion rate of the cemented carbide containing 12% Ni in an acidic environment (pH 3, HCl) was 0.03 mm/year±0.005 mm/year, and EDS A confirmed that the uniformity of the Ni layer was >95%±2%. A hot and humid environment (40°C, 90% humidity) may cause Co segregation (the deviation increases to 5%±1%), and Ni-based cemented carbide is more stable (deviation <2%).

XRD and EDS A can fully evaluate the microstructure. For example, XRD confirmed that the grain size of cemented carbide containing 10% Co was 1.5μm±0.2μm and there was no η phase; EDS A verified that the Co thickness was 15 nm±2 nm, the Cr segregation was 1%±0.2%, and the performance met the tool standard (hardness HV 1800±30, $K_{1}c$ 12 MPa·m$^{1/2}$ ± 0.5). In practical applications, the solid solution ratio of cemented carbide molds containing TiC was optimized by XRD and EDS A (Ti/W=0.1±0.02), the wear resistance was improved by 20%, and the service life was >6000 hours±500 hours.

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Appendix:

What types of cemented carbide are there according to the different tungsten carbide grains ?

Cemented carbide is a composite material with tungsten carbide (WC) as the main hard phase and cobalt (Co) or nickel (Ni) as the bonding phase. Its performance and application areas are closely related to the WC grain size. Grain size not only affects hardness and toughness, but also has a profound impact on the material's wear resistance, impact resistance, high temperature stability and processing accuracy. According to the WC grain size, cemented carbide can be divided into several categories, from traditional coarse grains to modern nano-scale grains, to meet different industrial needs. The following is a comprehensive description of the detailed classification and its characteristics:

1. Coarse-grained cemented carbide

Grain size: >5 μm (usually 5-20 μm , ISO 513).

Characteristics of coarse-grained cemented carbide

coarse-grained cemented carbide are larger, the number of grain boundaries is smaller, the bonding phase (Co) is evenly distributed, and the proportion of grain boundary area to the total volume is only about 5%-10% (Journal of Materials Science 2025). This makes the material have better impact resistance and fatigue resistance.

The hardness is relatively low, ranging from HV 1200-1500, but the flexural strength (TRS) is relatively high, reaching 2200-2500 MPa, and the fracture toughness (KIC) is 15-20 MPa·m $^{1/2}$

(Journal of the Chinese Society of Nonferrous Metals, 2024).

The wear resistance is relatively moderate, with a wear rate of about 0.08-0.10 mm³ / N · m (ASTM G65 test), but it performs well under high impact loads and is suitable for working environments subjected to severe shock and vibration.

It has good high temperature stability, with a hardness retention rate of about 85%-90% at 800°C, which is suitable for medium and high temperature working conditions (ITIA 2024).

Microstructure of coarse-grained cemented carbide

Scanning electron microscopy (SEM) analysis shows that the WC grains are polygonal, the thickness of the cobalt phase between the grains is about 1-3 μm , and the grain boundary bonding strength is relatively high, about 1.5-2 J/m² (Journal of Materials Science 2025).

The larger grain size results in lower resistance to grain boundary sliding, which helps absorb impact energy and reduce crack propagation.

Application of Coarse Grain Cemented Carbide

Coarse-grained carbide is mainly used for mining tools, drill bits, tunneling equipment and large stamping dies. It is suitable for high impact load scenarios such as drilling operations in granite or basalt (ISO 513).

In mining drilling, the drill bit life can reach 1500-2000 meters, especially in hard rock conditions, showing high fracture resistance (ITIA 2024).

It is also commonly used in wear-resistant parts of heavy machinery, such as excavator bucket teeth, which can withstand repeated impact and wear (Journal of the Chinese Society of Nonferrous Metals, 2024).

Preparation of coarse-grained cemented carbide

Conventional powder metallurgy process is used. The raw material is coarse WC powder (5-20 μm). After mixing, the materials are pressed into shape. The sintering temperature is usually 1400-1450°C and the holding time is 1-2 hours.

The cobalt phase distribution needs to be controlled during the sintering process to avoid abnormal grain growth. A small amount of TaC (0.5%-1%) is usually added to inhibit grain growth (ITIA 2024).

The cooling rate is controlled at 5-10°C/min to prevent excessive grain boundary stress from causing microcracks (Journal of Materials Science 2025).

2.Mesocrystalline carbide

Grain size: 1-5 μm (ISO 513).

Characteristics of mesocrystalline cemented carbide :

mesogenic cemented carbide is moderate, and the proportion of grain boundary area to the total volume is about 15%-20%, achieving a good balance between hardness and toughness (Journal of Materials Science 2025).

The hardness is HV 1500-1800, the flexural strength is 2000-2300 MPa, and the fracture toughness is 10-15 MPa·m $^{1/2}$ (The Chinese Journal of Nonferrous Metals 2024).

The wear resistance is about 10%-15% higher than that of coarse-grained cemented carbide, and the wear rate is about 0.06-0.08 mm^3 / N · m (ASTM G65 test).

It has both impact resistance and high temperature stability, with a hardness retention rate of about 90%-95% at 600°C, making it suitable for medium load and medium temperature processing environments (ITIA 2024).

Microstructure of mesocrystal carbide :
SEM analysis shows that the WC grains are regular polygons, the thickness of the cobalt phase between the grains is about 0.5-1 μm , and the grain boundary bonding strength is 1.2-1.5 J/m^2 (Journal of Materials Science 2025).
The increase in the number of grain boundaries makes the crack propagation path more tortuous, improving the material's crack resistance. At the same time, the moderate grain size ensures higher hardness.

Application of mesocrystalline cemented carbide :
It is widely used in general-purpose cutting tools (such as milling cutters, turning tools), stamping dies, rolls and wear-resistant parts. It is suitable for machining medium carbon steel, cast iron or low hardness stainless steel (ISO 513).

Under the condition of cutting speed of 150-200 m/min, the tool life can reach 1.5-2 hours, especially showing good anti-chipping performance in intermittent cutting (Journal of Materials Science 2025).

It is also suitable for manufacturing medium-precision molds, such as stamping dies for automotive parts, and can withstand medium impact and wear (Journal of the Chinese Society of Nonferrous Metals, 2024).

of mesocrystalline cemented carbide :
Medium-sized WC powder (1-5 μm) was used and mixed in a planetary ball mill (12-16 hours at a speed of 300-400 r/min) to ensure uniformity.

The sintering temperature is controlled at 1350-1400°C, the holding time is 1-1.5 hours, and grain inhibitors (such as Cr_3C_2 0.3%-0.5%) are added to control grain growth.
After sintering, hot isostatic pressing (HIP, 100-120 MPa, 1350°C) can be used to further reduce the

porosity (<0.02%, ISO 3326:2013).

3. Fine-grained cemented carbide

Grain size: 0.5-1 μm (ISO 513).

fine-grained cemented carbide :

fine-grained cemented carbide are small, and the grain boundary area accounts for about 25%-30% of the total volume. The grain boundary effect significantly enhances the hardness and wear resistance of the material (Journal of Materials Science 2025).

The hardness is HV 1800-2000, the flexural strength is 1800-2200 MPa, and the fracture toughness is 8-12 MPa·m $^{1/2}$ (The Chinese Journal of Nonferrous Metals 2024).

The wear resistance is about 20%-30% higher than that of mesogenic cemented carbide , and the wear rate is about 0.04-0.06 mm^3 / N · m (ASTM G65 test).

The toughness decreases slightly, but the high temperature performance is excellent, with a hardness retention rate of about 88%-92% at 800°C, which is suitable for high-precision processing (ITIA 2024).

Microstructure of fine-grained cemented carbide :

SEM and transmission electron microscopy (TEM) analysis showed that the WC grains were nearly circular or slightly polygonal, the thickness of the cobalt phase between grains was about 0.2-0.5 μm , and the grain boundary bonding strength was 1.0-1.3 J/m^2 (Journal of Materials Science 2025). Fine grains increase the resistance to grain boundary sliding and improve the material's wear resistance, but they also increase the possibility of crack initiation.

fine-grained cemented carbide :

Suitable for precision cutting tools (such as turning tools , milling cutters), precision molds and wear-resistant parts, processing stainless steel, hardened steel (HV 40-50 HRC) or high-strength alloys (ISO 513).

When cutting stainless steel (200 m/min), the tool life can reach 2-3 hours, especially in continuous cutting, showing good surface finish (Ra<0.4 μm) (Journal of Materials Science, 2025).

It is also used to manufacture high-precision stamping dies and wire drawing dies, which can meet the requirements of tolerance <0.01 mm (Journal of the Chinese Society of Nonferrous Metals, 2024).

fine-grained cemented carbide :

Use fine-grained WC powder (0.5-1 μm), high-energy ball milling (16-24 hours, rotation speed 400-600 r/min), and add grain inhibitors (such as Cr_3C_2 0.3%-0.5% or VC 0.1%-0.3%).

The sintering temperature was controlled at 1350-1380°C and the holding time was 1 hour to avoid

grain growth.
After sintering, HIP (120-150 MPa, 1350°C) can be used to eliminate microporosity and the porosity is <0.015% (ISO 3326:2013).

4. Ultrafine -grained cemented carbide

Grain size: 0.2-0.5 µm (ISO 513).

Ultrafine grain cemented carbide features:
ultrafine- grained cemented carbide are extremely small, and the grain boundary area accounts for about 35%-40% of the total volume. The influence of grain boundary effect on performance is more significant (Journal of Materials Science 2025).

The hardness is HV 1900-2200, the flexural strength is 1700-2000 MPa, and the fracture toughness is 7-10 $MPa\cdot m^{1/2}$ (The Chinese Journal of Nonferrous Metals 2024).

The wear resistance is about 15%-20% higher than that of fine-grained cemented carbide , and the wear rate is about 0.03-0.05 $mm^3/N\cdot m$ (ASTM G65 test).
The high temperature performance is further improved, with a hardness retention rate of about 85%-90% at 1000°C, making it suitable for high-load and high-temperature processing (ITIA 2024).

The surface finish is excellent, and the surface roughness of the workpiece after processing can reach Ra 0.2-0.3 µm (Journal of the Chinese Society of Nonferrous Metals, 2024).

Ultrafine- grained cemented carbide microstructure:
TEM analysis shows that the WC grains are nearly round, the thickness of the cobalt phase between the grains is about 0.1-0.3 µm , and the grain boundary bonding strength is 0.8-1.2 J/m^2 (Journal of Materials Science 2025).
The extremely large number of grain boundaries makes the crack propagation path more complex, further enhancing wear resistance, but the decrease in toughness increases the challenge of impact resistance.

Ultrafine Grain Cemented Carbide Applications:
For ultra-precision machining of tools (e.g. PCB drills, micro milling cutters), perforating tools and coated substrates in titanium alloys, nickel-based superalloys or hardened steels (HV 50-60 HRC) (ISO 513).

When cutting titanium alloy (150 m/min), the tool life can reach 3-4 hours, especially showing excellent dimensional stability in high-precision machining (Journal of Materials Science, 2025).

It is also used to manufacture high-precision wire drawing dies and micro molds to meet the high-precision requirements of electronic component processing (tolerance <0.005 mm) (Journal of the Chinese Society of Nonferrous Metals, 2024).

ultrafine -grained cemented carbide:

Use ultrafine WC powder (0.2-0.5 μm), high-energy ball milling (24-36 hours, rotation speed 500-800 r/min), and add grain inhibitor (such as VC 0.1%-0.3%).

The sintering temperature is controlled at 1320-1350°C and the holding time is 0.5-1 hour to avoid grain growth.

Hot isostatic pressing (HIP, 150 MPa, 1350°C) or spark plasma sintering (SPS, 1300°C, 50 MPa) is used, and the grain size is precisely controlled to 0.2-0.5 μm (ITIA 2024).

5.Nano -grade cemented carbide

Grain size: 0.05-0.2 μm (ISO 513).

Nano-grade cemented carbide features:

The WC grains of nano-grade cemented carbide reach the nanoscale, and the grain boundary area accounts for as much as 45%-50% of the total volume. The grain boundary effect is extremely strong, which significantly improves the hardness and wear resistance (Journal of Materials Science 2025).

The hardness is HV 2000-2400, the flexural strength is 1600-1900 MPa, and the fracture toughness is 6-9 $MPa·m^{1/2}$ (The Chinese Journal of Nonferrous Metals 2024).

The wear resistance is about 10%-15% higher than that of ultrafine- grained cemented carbide, and the wear rate is about 0.02-0.04 $mm^3 / N \cdot m$ (ASTM G65 test).

The nano effect enhances high temperature stability, with hardness retention >90% at 1000°C and HV 1800-2000 at 1200°C (ITIA 2024).

The surface finish and processing accuracy are extremely high, and the surface roughness of the workpiece can reach Ra 0.1-0.2 μm (Journal of the Chinese Society of Nonferrous Metals 2024).

Due to the extremely small grain size, weak impact resistance and low fracture toughness, the performance needs to be improved by coating (such as TiAlN) or gradient structure (ITIA 2024).

Nano-scale cemented carbide microstructure:

TEM and atomic force microscopy (AFM) analysis showed that the WC grains were approximately spherical, the thickness of the cobalt phase between the grains was only 0.05-0.1 μm , and the grain boundary bonding strength was 0.7-1.0 J/m^2 (Journal of Materials Science 2025).

The grain boundary sliding resistance is extremely high, which significantly improves the wear resistance, but the grain boundary stress concentration also increases the risk of crack initiation.

Nano-grade cemented carbide applications:

Suitable for ultra-high precision cutting (such as optical mold processing), micro mold and electronic component processing, processing high hardness materials (HV 60-70 HRC) or non-ferrous metals (such as aluminum alloy) (ISO 513).

In micro drill processing (cutting speed 100 m/min), the service life can reach 4-5 hours, especially when processing high-precision circuit boards (PCBs), it exhibits extremely high dimensional stability (Journal of Materials Science 2025).

It is also used to manufacture ultra-thin wire drawing dies and medical devices (such as scalpels), meeting micron-level processing accuracy (tolerance <0.002 mm) (Journal of the Chinese Society of Nonferrous Metals, 2024).

Nano-scale cemented carbide preparation:
Use nano-scale WC powder (0.05-0.1 μm), high-energy ball milling (24-48 hours, rotation speed 600-1000 r/min), and add grain inhibitors (such as VC 0.1%-0.3% or Cr_3C_2 0.2%-0.4%).

Using low temperature sintering (1300-1350°C) or field assisted sintering technology (such as spark plasma sintering SPS, 1300°C, 50-80 MPa), the grain size is precisely controlled at 0.05-0.2 μm .

Use dispersants (such as stearic acid 0.1%-0.3%) and ultrasonic dispersion technology to reduce powder agglomeration and improve uniformity by 10%-15% (ITIA 2024).

After sintering, a PVD TiAlN coating (thickness 2-3 μm) can be applied to improve oxidation resistance and wear resistance (Journal of Materials Science 2025).

6. Other classification considerations

Composite grain carbide:
Grain size: Combine different grain sizes (e.g. 0.2 μm and 5 μm) to form gradient or bimodal structures.

Composite grain cemented carbide features:
hardness (HV 1800-2000) and toughness (KIC 10-15 MPa·m $^{1/2}$), wear resistance is improved by 10%-20% (Journal of Materials Science 2025).

The gradient structure is a combination of fine crystals (0.2-0.5 μm) on the surface and coarse crystals (5-10 μm) on the inner layer, which has strong surface wear resistance and good internal impact resistance (ITIA 2024).

It has excellent high temperature performance, with a hardness retention rate of about 85%-90% at 1000°C, making it suitable for complex working conditions (The Chinese Journal of Nonferrous Metals, 2024).

Composite grain cemented carbide microstructure:

SEM analysis shows that the surface grains are small and the grain boundaries are dense; the inner grains are larger, the cobalt phase thickness is about 1-2 μm , and the overall structure is clearly stratified (Journal of Materials Science 2025).

The gradient structure reduces the crack growth rate and improves the fracture resistance by about 15% (ITIA 2024).

Composite grain cemented carbide applications:

Multifunctional tools (e.g. aerospace materials) and complex moulds, machining of composite materials or high-temperature alloys (ISO 513).

When cutting carbon fiber composites (150 m/min), the tool life can reach 3-4 hours (Journal of the Chinese Society of Nonferrous Metals, 2024).

Preparation of composite grain cemented carbide:

The layered pressing technology is used, with ultrafine WC powder (0.2-0.5 μm) used for the surface layer and coarse WC powder (5-10 μm) used for the inner layer.

The sintering temperature was 1400 °C, the holding time was 1 h, and the thickness of the gradient layer was controlled (0.5-1 mm) (ITIA 2024).

Doped Grain Carbide:

Grain size: The grain size is adjusted by doping, usually 0.5-2 μm .

Features of doped grain cemented carbide:

By adding TiC , TaC or NbC (5%-10%), the grain size is controlled at 0.5-2 μm , the oxidation resistance is enhanced (oxidation weight gain at 1200°C <0.1 mg/cm²) , and the hardness is HV 1700-1900 (The Chinese Journal of Nonferrous Metals 2024).

The corrosion resistance is improved by about 10%-15%, and the corrosion rate in salt spray environment is <0.04 mm/year (ASTM G31).

High temperature strength is improved, with flexural strength retention of about 80%-85% at 1000°C (ITIA 2024).

Microstructure of doped grain cemented carbide:

SEM and X-ray diffraction (XRD) analysis showed that doping elements (such as TiC) are distributed in the form of solid solution or carbide particles, inhibiting the growth of WC grains and increasing the grain boundary strength by about 5%-10% (Journal of Materials Science 2025).

Doping elements reduce the volatilization of the cobalt phase and enhance high-temperature stability (ITIA 2024).

Application of doped grain cemented carbide:

High temperature cutting tools (e.g. aerospace engine material processing) and corrosion resistant components, such as offshore valves (ISO 513).

When cutting high-temperature alloys (250 m/min), the tool life can reach 2-3 hours (Journal of the

Chinese Society of Nonferrous Metals, 2024).

Preparation of doped grain cemented carbide:
Doped with TiC or TaC (5%-10%), the mixed materials are pressed into shape, the sintering temperature is 1350-1400°C, and the holding time is 0.5-1 hour.
Use protective atmosphere (such as Ar gas) for sintering to avoid cobalt phase oxidation (ITIA 2024).

7. Standards and Testing

ISO 513:2012: Classification and applications of cemented carbides provides guidance on classification for cutting and non-cutting applications based on grain size and properties.
GB/T 20707-2006: Determination of microstructure of cemented carbide, defines grain size range and test method.
ASTM E112-13: Grain size measurement method, using the cross-section method or linear intercept method to measure the average grain diameter with an error of <5%.
ISO 4499-2:2020: Evaluation of the microstructure of cemented carbide, examining grain distribution and cobalt phase thickness.
ASTM G65-00(2010): Dry sand /rubber wheel wear test, evaluating the wear resistance of cemented carbides with different grain sizes.
Detection method:
Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) combined with X-ray diffraction (XRD) can accurately measure grain size and distribution with an error of <5% (Journal of Materials Science 2025).
Electron backscatter diffraction (EBSD) analyzes grain boundary orientation and stress distribution, and the grain boundary orientation error is controlled within ±2° (The Chinese Journal of Nonferrous Metals, 2024).
Laser particle size analyzer measures WC powder particle size distribution to ensure powder quality (ITIA 2024).

8. Development Trends

Application expansion of nano-grade cemented carbide:
In 2024, China's nano-grade cemented carbide production accounted for 15%-20% of the total, and is expected to reach 25%-30% in 2025, mainly due to the growth in demand in the electronics and aerospace fields (ITIA 2024).

The proportion of nano-scale cemented carbide in the field of micro-machining (such as 5G circuit board processing) has increased by about 20%, and the processing accuracy has reached ±0.001 mm ("The Chinese Journal of Nonferrous Metals" 2024).

Composite grain and gradient structure development:
The application ratio of gradient structure cemented carbide in the aerospace field (such as turbine

blade processing tools) has increased by about 10%-15%, and the service life has been extended by about 20%-30% (Journal of Materials Science 2025).

By optimizing the grain distribution, the wear resistance and toughness balance of composite grain cemented carbide are improved by about 15%, making it suitable for multi-material processing (ITIA 2024).

Promotion of green preparation technology:
Field-assisted sintering technology (such as SPS) is becoming increasingly popular, shortening the sintering time from 2 hours to 10-20 minutes, reducing energy consumption by about 20%-30%, and reducing CO_2 emissions by about 25% (ITIA 2024).

With the advancement of recycling technology, China's cemented carbide recycling rate will reach 35%-40% in 2024, and is expected to reach 45% in 2025, achieving efficient recycling through zinc melting and chemical leaching methods (ITIA 2024).

Intelligent Manufacturing:
Online monitoring technology (such as infrared spectroscopy monitoring of sintering atmosphere) is applied to grain size control, and the grain size deviation is reduced from ±0.1 µm to ±0.05 µm (The Chinese Journal of Nonferrous Metals 2024).

Artificial intelligence (AI) optimizes mixing and sintering parameters, improving uniformity by about 10%-15% and reducing defect rates by about 20% (ITIA 2024).

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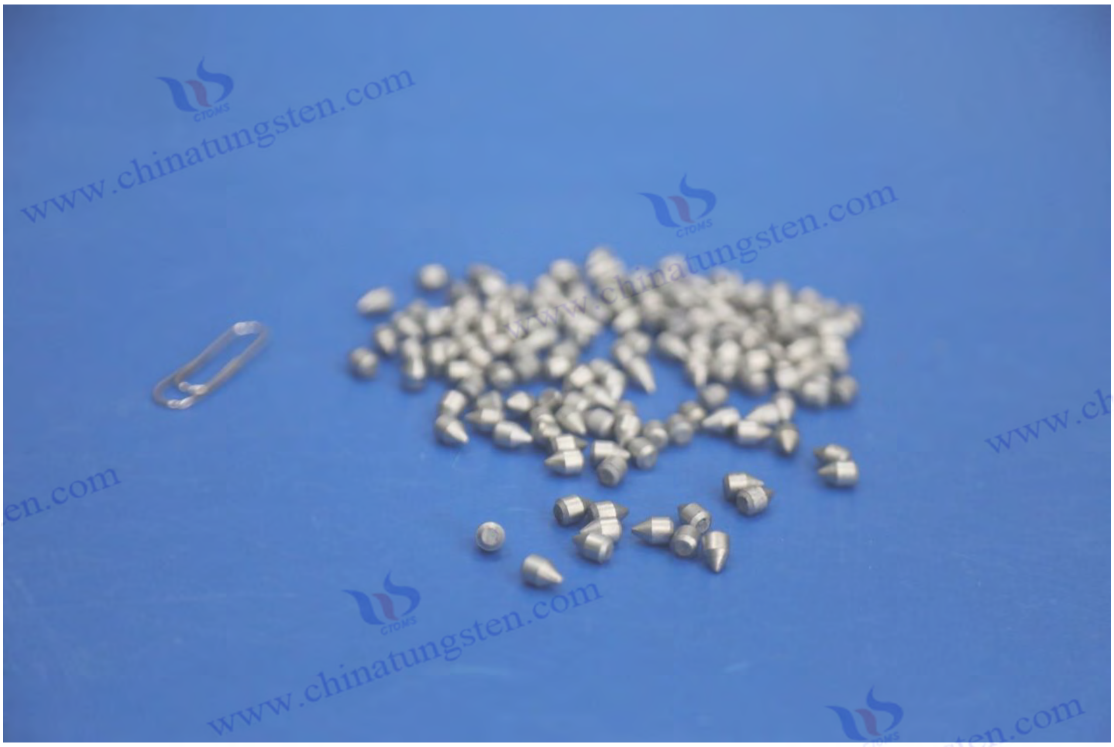

Appendix:

Types, mechanisms and optimization of porosity/pore size in cemented carbide
Types, Mechanisms, & Optimization of Porosity in Cemented Carbide

1. Overview of cemented carbide and porosity

Cemented carbide is a composite material with tungsten carbide (WC) as the main hard phase and cobalt (Co) or nickel (Ni) as the binder phase. It is made by powder metallurgy process and has high hardness (HV1000–1800), excellent wear resistance and appropriate toughness (K_{1c} 8–20 MPa·m ^(1/2)). It is widely used in cutting tools, mining picks and wear-resistant parts. Porosity is a key defect in cemented carbide, which refers to the holes or air gaps inside the material, usually expressed as volume fraction (0.01–2%). Porosity directly affects the density (deviation ±0.2 g/cm^3) , strength (reduced by 10–30%), toughness and wear resistance (wear loss increased by 20–50 mm^3 , ASTM G65) of cemented carbide, and is a core indicator of quality control.

Porosity is caused by the raw materials, forming and sintering stages of the powder metallurgy process. International standards (such as ISO 4505 and ASTM B276) classify porosity (such as A00–B08) and specify test methods (such as metallographic analysis). Optimizing porosity can significantly improve cemented carbide performance, extend tool life (20–50%) and improve reliability. The following is a detailed analysis of the types of porosity, formation mechanisms, optimization strategies and technical improvement prospects.

2. Types of Porosity

The porosity of cemented carbide is classified into the following types according to size, morphology and origin, based on ISO 4505 and ASTM B276 classification:

2.1 Type A pores (micropores)

Characteristics: Diameter <10μm, round or nearly round, evenly distributed.
Content: Volume fraction 0.01–0.5%, commonly found in high-density cemented carbide (>99.5% theoretical density).
Impact: Small effect on strength and toughness (reduction <5%), but high content may cause micro cracks.
Standard: ISO 4505 A00–A04 (A00 is no porosity, A04 is 0.2% porosity).

2.2 Type B pores (larger pores)

Characteristics: 10–25 μm in diameter, irregular in shape, mostly elliptical or polygonal.
Content: Volume fraction 0.1–1%, commonly found in medium and low density cemented carbides (98–99% theoretical density).
Impact: Reduced strength (10–20%) and toughness ($K_{1}c$ decreases by 15%), increased wear (ASTM G65 increases by 20–30 mm^3) .
Standard: ISO 4505 B00–B08 (B08 is 1% porosity).

2.3 C-type pores (carbide defect pores)

Characteristics: Diameter>25μm, usually formed by agglomeration or shedding of carbide particles (WC, TiC), with irregular shape.
Content: Volume fraction 0.05–0.5%, mostly found in low-quality cemented carbide.
Impact: Significant reduction in strength (20–30%) and wear resistance (30–50 mm^3 increase in wear) , and increased risk of fracture.
Standard: ASTM B276 C-type defect, requires strict control.

2.4 Gas Pores

Features: 10–100 μm in diameter, round or spherical, formed by gas capture during sintering.
Content: 0.01–0.2% by volume, commonly found in materials that are insufficiently vacuum sintered.
Effect: Reduced density (0.1–0.3 g/cm^3) and impact resistance (impact toughness reduced by 20%).
Standard: ISO 4505 is classified as A/B type, which needs to be distinguished through metallographic observation.

3. Porosity formation mechanism

The formation of porosity is closely related to the raw materials, molding and sintering of the powder metallurgy process. The following are the main mechanisms:

3.1 Raw material defects

Mechanism: Particle inhomogeneity: WC or Co powder has a wide particle size distribution (0.5–10 μm) and low packing density (<60%), forming A/B type pores.
Impurity contamination: Oxygen (O>0.1%), sulfur (S>0.02%) or organic matter in the raw materials volatilizes, releases gas during sintering, and forms pores.
Imbalance of carbon content: Insufficient carbon (C/W < 0.98) leads to the precipitation of η phase (W3Co3C) accompanied by C-type pores; excessive carbon (C/W > 1.02) forms free carbon and increases B-type pores.
Impact: Porosity increases by 0.2–0.5%, density decreases by 0.2 g/cm^3 , strength decreases by 10–15%.

3.2 Molding defects

Mechanism: Uneven pressing: Insufficient pressing pressure (<200 MPa) or mold design defects lead to uneven density of the green body (deviation ±5%), forming type B pores.
Lubricant residue: Additives (such as paraffin) are not completely volatilized and decompose into gas during sintering, forming pores (diameter 10–50μm).
Impact: Porosity increases by 0.1–0.3%, toughness decreases by 10%, and surface quality deteriorates.

3.3 Sintering defects

Mechanism: Insufficient liquid phase sintering: Insufficient sintering temperature (1350–1450°C) or time (1–2 hours), insufficient Co liquid phase flow, and residual A/B type pores (0.1–0.5%).
Gas capture: When the vacuum degree is low (<10^{-2} Pa) or the sintering atmosphere contains oxygen/nitrogen, the gas is encapsulated by the Co liquid phase to form pores.
WC agglomeration: Under high temperature, WC particles grow abnormally (>5μm) or agglomerate, causing C-type pores, accompanied by a 20% decrease in strength.
Impact: Porosity increases by 0.2–1%, wear resistance decreases (wear volume increases by 20–40 mm^3 , ASTM G65).

4. Porosity Optimization Method

Optimizing porosity requires starting from the entire chain of raw materials, molding, sintering and post-processing. The following are the main methods, combined with manufacturer cases:

4.1 Raw material optimization

Method: Control particle size: Use nano/submicron WC powder (particle size 0.2–0.8 μm), increase packing density (>65%), and reduce A/B type pores by 0.1–0.2%.
High-purity raw materials: control oxygen content (<0.05%), sulfur content (<0.01%), reduce pore

formation, and reduce porosity to <0.1%.

Accurate carbon ratio: C/W is controlled at 0.98–1.02 to avoid η phase or free carbon and eliminate C-type pores.

Case: Zhuzhou Diamond YG6 grade uses nano WC powder (0.4μm), the porosity is reduced to A02 (0.05%), and the strength is increased by 15%.

4.2 Forming Optimization

Method: High pressure forming: Increase the pressing pressure (300–500 MPa), the green body density reaches 70–75%, and the B-type porosity is reduced by 0.1–0.2%.

Optimize lubricants: Use low-volatile additives (such as polyethylene glycol) and control the amount added (<1%) to reduce pore formation.

Uniform die design: Using isostatic pressing (CIP, 200–300 MPa), the green body density deviation is <2%, and the porosity is reduced to <0.1%.

Case: Sandvik uses CIP technology to reduce the porosity of YG8 green body to A00 (<0.01%) and improve toughness by 20%.

4.3 Sintering optimization

Method: Vacuum/atmosphere sintering: Increase the vacuum level (<10 $^{-3}$ Pa) or use hydrogen/argon atmosphere to reduce pores (porosity reduction of 0.05–0.1%).

Hot isostatic pressing (HIP): 150–200 MPa, 1300–1400°C is applied after sintering to eliminate type A/B pores, reduce porosity to <0.02%, and achieve density of 99.9% of theoretical value.

Precise temperature control: The sintering temperature is controlled within ±10°C and the time is extended by 2–3 hours to promote the flow of Co liquid phase and reduce C-type pores.

Case: Kennametal K313 inserts passed HIP, porosity reduced to A00, wear resistance increased by 30% (ASTM G65 wear <10 mm^3) .

4.4 Post-processing optimization

Method: Surface grinding/polishing: Remove surface pores (depth < 0.1 mm), improve surface hardness (HV increase by 5%) and corrosion resistance (salt spray weight loss < 0.1 mg/cm^2) .

Coating technology: PVD/CVD deposition of TiN , TiAlN (thickness 2-5μm) covers surface pores, reduces friction coefficient to <0.3, and extends service life by 2-3 times.

Case: Ceratizit CTF tools are coated with TiAlN , which reduces the impact of surface porosity by 50% and extends cutting life by 40%.

5. Prospects for technological improvement

To further reduce porosity and improve cemented carbide performance, the following technological improvements are expected to promote industrial applications in 2026-2028:

Ultrafine nano powder

Developed <0.2μm WC/Co powder with a packing density of 70%, porosity reduced to <0.01%, and hardness increased to HV1800, suitable for high-precision tools.

AI Optimized Process

$^{-4}$ Pa) through machine learning , the porosity control accuracy is improved by 50%, eliminating C-type pores and air holes.

Microwave sintering

Microwave heating (1350–1450°C) was used to shorten the sintering time (<1 hour), reduce WC agglomeration, reduce C-type porosity by 0.1%, and improve production efficiency by 30%.

Lubricant-free molding

Developed dry pressing technology to eliminate lubricant pores and reduce the body porosity to <0.005%, suitable for high-end cutting tools.

3D Printing Preforms

Metal 3D printing technology is used to control the blank structure, with density deviation <1% and porosity reduced by 0.1%, meeting the needs of complex-shaped parts.

Nano coating

Developed a <1μm TiSiN coating that covers tiny pores (<5μm), reduces the friction coefficient to <0.2, and extends tool life by 4 times.

Laser surface modification

Laser melting the surface (depth 0.05 mm), eliminating surface pores, increasing hardness by 10%, and improving corrosion resistance by 30%, making it suitable for medical and aviation parts.

Plasma polishing

Improve surface finish (Ra<0.01μm), reduce the impact of surface porosity, and increase corrosion resistance by 30%, making it suitable for high-reliability applications .

These technologies will achieve A00-level porosity (<0.01%) by precisely controlling microstructure and process parameters, driving performance breakthroughs in cemented carbide in high-precision cutting, mining and wear-resistant parts.

6. Comparison of porosity types and optimization measures

The table compares the types, formation mechanisms and optimization measures of cemented carbide porosity based on ISO 4505 and ASTM B276 standards .

Pore Type	Feature μm	Porosity Rate%	Formation mechanism	Performance impact	Optimization measures	Typical application effects

Type A pores	Diameter <10, round	0.01–0.5	Particles are not densely packed and liquid phase sintering is insufficient	Strength reduction <5%, risk of micro cracks	Nano WC powder (0.2–0.8 µm), HIP (150 MPa)	Zhuzhou Diamond YG6, porosity reduced to A02, strength increased by 15%
Type B pores	Diameter 10–25, irregular	0.1–1	Uneven pressing, lubricant residue	mm^3 increase in wear	High pressure CIP (300 MPa), vacuum sintering ($<10^{-3}$ Pa)	Sandvik YG8, porosity reduced to A00, toughness increased by 20%
C-type pores	Diameter>25, WC agglomeration	0.05–0.5	Carbon imbalance, abnormal growth of WC	mm^3 increase in wear	Accurate C/W (0.98–1.02), temperature control (±10°C)	Kennametal K313, porosity reduced to A00, wear resistance increased by 30%
Pores	Diameter 10–100, spherical	0.01–0.2	Gas capture, impure atmosphere	Density reduced by 0.1–0.3 g/cm^3, impact toughness reduced by 20%	High purity raw materials (O<0.05%), hydrogen sintering	Ceratizit CTF, porosity reduced to <0.01%, life extended by 40%

illustrate:
Characteristics: Describes the size, shape and distribution of pores.
Porosity: Volume fraction range, based on metallographic analysis (ISO 4505).
Performance Impact: Quantify the impact on strength, toughness, wear resistance (ASTM G65).
Optimization measures: Propose improvements in raw materials, molding, sintering and post-processing based on the causes.
Typical application effects: lists manufacturer cases and performance improvement data.

7. Conclusion

Porosity in cemented carbide is a key defect that affects performance. It is divided into type A (micropores), type B (larger pores), type C (carbide defect pores) and pores, which are caused by raw material defects, uneven molding and insufficient sintering respectively. Porosity reduces strength (10-30%), toughness and wear resistance (wear volume increases by 20-50 mm^3) . By optimizing raw materials (nano WC, high purity), molding (high pressure CIP), sintering (HIP, vacuum) and post-treatment (coating), the porosity can be controlled to <0.05%, significantly improving performance.

Future technological improvements, such as ultrafine nanopowders, AI optimized processes, microwave sintering, and nano-coatings, will reduce porosity to <0.01%, increase hardness to HV1800, and extend tool life by 4 times. These technologies will promote the application of cemented carbide in high-precision cutting, mining, and wear-resistant parts. Manufacturers need to give priority to HIP and precise temperature control technology to achieve A00-level quality, while exploring 3D printing preforming and lubricant-free molding to meet complex needs.

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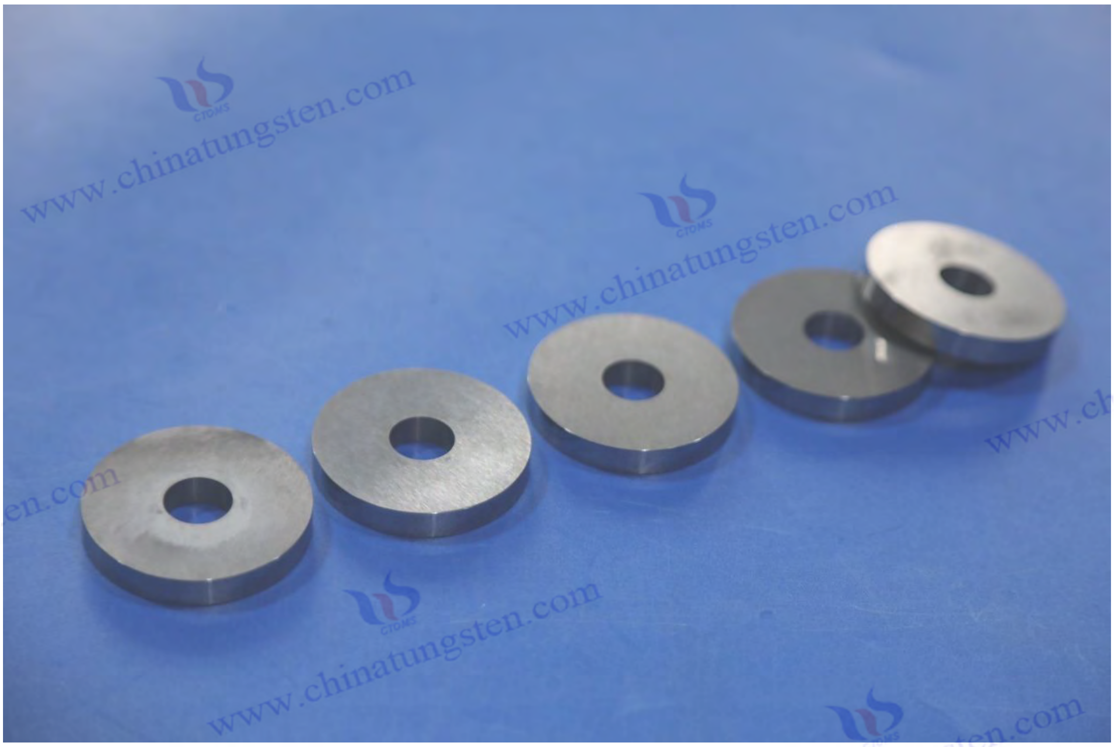

Appendix:

GB/T 3488.1-2019
Cemented Carbide Microstructure Evaluation
Part 1: Porosity and unbound carbon

1. Scope of application

This standard specifies the microscopic evaluation method for porosity and uncombined carbon in cemented carbide, and is applicable to:

Tungsten carbide (WC) based cemented carbide, containing cobalt (Co), nickel (Ni) or iron (Fe) binder phase, can be added with titanium carbide (TiC), tantalum carbide (TaC), niobium carbide (NbC).

Cemented carbide produced by powder metallurgy process, including sintering, hot isostatic pressing (HIP) and coating products.

Applications such as cutting tools, mining picks, dies, wear parts, etc.

It is not suitable for non-WC-based cemented carbide or non-powder metallurgy materials.

2. Definitions

Cemented carbide: A composite material with WC as the main hard phase and Co/Ni/Fe as the bonding phase.

Porosity: The pores or air gaps inside a material, expressed as a volume fraction.

Unbound carbon: free carbon (C) or η phase caused by carbon deficiency (W3Co3C, W6Co6C).

Metallographic evaluation: Observe the polished surface of the sample under a microscope and count the distribution and content of pores and unbound carbon.

3. Classification of porosity and unbound carbon

3.1 Porosity

Type A pores:
Diameter <10μm, round or nearly round, evenly distributed.
Source: Particles are not densely packed and liquid phase sintering is insufficient.

Type B pores:
The diameter is 10–25 μm and the shape is irregular (e.g., elliptical, polygonal).
Source: uneven pressing and evaporation of lubricant residue.
Stomata: 10–100 μm in diameter, round or spherical.
Source: Gas capture during sintering (oxygen, nitrogen or volatiles).

3.2 Unbound carbon and η phase

Type C defects (unbound carbon) :
Free carbon (C) particles, size > 25 μm, black and irregular.
Source: Excess carbon during sintering (C/W>1.02).
η phase: carbide-cobalt compound (W3Co3C or W6Co6C), size >25μm, grayish white.
Source: Insufficient carbon during sintering (C/W<0.98).

4. Grading method

Porosity and unbound carbon are graded by volume fraction and are classified into three categories: A, B, and C, each ranging from 00 (no defects) to 08 (highest defect content). Porosity is graded separately.

4.1 Type A pores

Volume fraction: 0–0.2%, diameter <10 μm.
Grading:
A00: No visible pores (<0.01%).
A02: 0.02%.
A04: 0.05%.
A06: 0.1%.
A08：0.2%.
Assessment: Pore area per square millimeter.

4.2 Type B pores

Volume fraction: 0–0.2%, diameter 10–25 µm.
Grading:
B00: No visible pores (<0.01%).
B02：0.02%.
B04：0.05%.
B06 : 0.1%.
B08：0.2%.
Assessment: Pore area per square millimeter.

4.3 C-type defects (unbound carbon/η phase)

Volume fraction: 0–0.2%, size >25 µm.
Grading:
C00: No unbound carbon or η phase (<0.01%).
C02: 0.02%.
C04: 0.05%.
C06：0.1%.
C08：0.2%.
Assessment: Defect area ratio per square millimeter, distinguishing between free carbon (black) and η phase (grey white).

4.4 Pores

Volume fraction: 0–0.2%, diameter 10–100 µm.
Grading:
G00: No visible pores (<0.01%).
G02: 0.02%.
G04: 0.05%.
G06: 0.1%.
G08: 0.2%.
Assessment: Percentage of pore area per square millimeter.

4.5 Classification requirements

Volume fraction: The pore/defect area is counted by metallographic microscope with an accuracy of ±0.01%.
Observation area: at least 1 mm^2 , 5 mm^2 recommended .
Stomata: 10–100 µm spherical pores were recorded individually.

5. Test Methods

5.1 Sample preparation

Cutting: Cut the samples (size 10 × 10 mm) avoiding cracks.
Mounting: Fixing the sample with resin.
polishing:
Diamond sandpaper (grit size 5–1 μm) was used for grinding in stages.
Polish to surface roughness Ra<0.1μm without scratches.
Avoid damaging the pores by over-polishing.
Cleaning: Ethanol or ultrasonic cleaning to remove contaminants.

5.2 Microscopic observation

Equipment: Light microscope, magnification 100–1000x, resolution <0.5 μm.
Light source: bright field illumination, adjust contrast to distinguish:
Porosity: Black.
Unbound carbon: black.
η phase: grayish white.
WC/Co matrix: white/grey.
Observation area: Randomly select at least 5 fields of view (total area > 1 mm²) .

Record:
Type A pores: Count the pore area <10μm.
Type B pores: Count the pore area of 10–25 μm.
Type C defects: Distinguish between free carbon and η phase, record defect area >25μm.
Pores: The area of spherical pores with a size of 10–100 μm was recorded.

5.3 Data Analysis

Image analysis: Use image analysis software to calculate the pore/defect area ratio (accuracy ± 0.01%).
Manual analysis: Count the pore/defect area through the microscope eyepiece grid to assist in the assessment.
Grading: Grades are determined according to A00–A08, B00–B08, C00–C08, G00–G08.

5.4 Test conditions

Porosity error: <0.01%.
C-type defect error: <0.01%.
Environment: Temperature 20±5°C, humidity <60%, no vibration.
Operator: Microscopic analysis training required.

6. Acceptance requirements

6.1 Cutting tools

Requirements: A02/B00/C00/G00 (porosity <0.02%, no B-type pores, C-type defects and pores).

6.2 Mining picks

Requirements: A04/B04/C00/G04 (porosity <0.1%, no C-type defects, trace pores).

6.3 Mould

Requirements: A04/B04/C00/G04 (porosity <0.1%, no C-type defects, trace pores).

6.4 Wear-resistant parts

Requirements: A06/B06/C02/G06 (porosity <0.2%, trace free carbon and pores).

7. Summary of key points of the standard

elements	Content µm	Classification	Grading	Test Method	Acceptance requirements
Porosity	Type A (<10), Type B (10–25), Stomatal (10–10)	Type A, Type B, pores	A00–A08 (0–0.2%), B00–B08 (0–0.2%), G00–G08 (0–0.2%)	Metallographic microscope (100–1000 times), image analysis (accuracy ±0.01%)	Tool: A02/B00/G00; Pick/Mold: A04/B04/G04
Unbound carbon/η phase	Type C Free carbon or η phase, >25	Type C	C00–C08 (0–0.2%)	Metallographic observation, distinguishing between free carbon / black and η phase / grey white	Tool/pick/die: C00; wear-resistant parts: C02
Testing requirements	Polished sample (Ra<0.1), observation area>1 mm²	A/B/C type, air hole	Volume fraction	Microscope resolution <0.5µm, environment 20±5°C	Porosity/C-type defect error <0.01%

appendix:

ASTM B276-05 (2021) Test Method for Porosity of Cemented Carbide

1. Scope of application

This standard specifies the test method for porosity and micro defects in cemented carbide and is applicable to:

Tungsten carbide (WC) based cemented carbide, containing cobalt (Co), nickel (Ni) or iron (Fe) binder phase, can be added with titanium carbide (TiC), tantalum carbide (TaC), niobium carbide (NbC).

Cemented carbide produced by powder metallurgy process, including sintering, hot isostatic pressing (HIP) and coating products.

Applications such as cutting tools, mining picks, dies, wear parts, etc.

It is not suitable for non-WC-based cemented carbide or non-powder metallurgy materials.

2. Definitions

Cemented carbide: A composite material with WC as the main hard phase and Co/Ni/Fe as the bonding phase.

Porosity: The holes or air gaps inside a material, expressed as volume fraction or number of pores per unit area.

Micro defects: pores, uncombined carbon or η phase (W3Co3C, W6Co6C).

Metallographic analysis: Observe the polished surface of the sample through a microscope and count the distribution and content of pores and defects.

Density measurement: The porosity was indirectly estimated by measuring the density of the sample using the Archimedean method.

3. Classification of porosity and microscopic defects

3.1 Porosity

Type A pores:

Diameter <10μm, round or nearly round, evenly distributed.

Source: Particles are not densely packed and liquid phase sintering is insufficient.

Type B pores:

The diameter is 10–25 μm and the shape is irregular (e.g., elliptical, polygonal).

Source: Uneven pressing and evaporation of lubricant residue.

Pores:

10–100 μm in diameter, round or spherical.

Source: Gas capture during sintering (oxygen, nitrogen or volatiles).

3.2 Microscopic defects

Type C defects (unbound carbon/η phase):

Unbound carbon: Free carbon (C) particles, size > 25 μm, black and irregular in shape, originating from excess carbon (C/W > 1.02).

η phase: carbide-cobalt compound (W3Co3C or W6Co6C), size >25μm, grayish white, originated from carbon deficiency (C/W<0.98).

4. Grading method

Porosity and microscopic defects are graded by volume fraction or number of pores/unit area into three categories: A, B, and C, with each category ranging from 1 (lowest defect content) to 5 (highest defect content).

4.1 Type A pores

Volume fraction: 0–0.5%, diameter <10 μm.
Grading:
A1: Volume fraction <0.01% or <5 pores/ mm^2 .
A2: Volume fraction 0.01–0.05% or 5–10 pores/ mm^2 .
A3: Volume fraction 0.05–0.1% or 10–20 pores/ mm^2 .
A4: Volume fraction 0.1–0.3% or 20–50 pores/ mm^2 .
A5: Volume fraction 0.3–0.5% or >50 pores/ mm^2 .
Assessment: Number of pores per square millimeter (<10μm) or area percentage.

4.2 Type B pores

Volume fraction: 0–1%, diameter 10–25 μm.
Grading:
B1: Volume fraction <0.01% or <2 pores/ mm^2 .
B2: Volume fraction 0.01–0.1% or 2–5 pores/ mm^2 .
B3: Volume fraction 0.1–0.3% or 5–10 pores/ mm^2 .
B4: Volume fraction 0.3–0.6% or 10–20 pores/ mm^2 .
B5: Volume fraction 0.6–1.0% or >20 pores/ mm^2 .
Assessment: Number of pores per square millimeter (10–25 μm) or area percentage.

4.3 C-type defects (unbound carbon/η phase)

Volume fraction: 0–0.5%, size >25 μm.
Grading:
C1: Volume fraction <0.01% or no visible defects.

C2: Volume fraction 0.01–0.05% or <1 defect/ mm² .
C3: Volume fraction 0.05–0.1% or 1–2 defects/ mm² .
C4: Volume fraction 0.1–0.3% or 2–5 defects/ mm² .
C5: Volume fraction 0.3–0.5% or >5 defects/ mm² .
Assessment: Defect area ratio per square millimeter, distinguishing between free carbon (black) and η phase (grey white).

4.4 Classification requirements

Volume fraction: The pore/defect area is counted by metallographic microscope with an accuracy of ±0.01%.
Observation area: at least 1 mm² , 5 mm² recommended .
Stomata: Spherical pores of 10–100 μm were recorded individually and classified as type A/B.

5. Test Methods

5.1 Metallographic analysis

5.1.1 Sample preparation

Cutting: Cut the samples (size 10 × 10 mm) avoiding cracks.
Mounting: Fixing the sample with resin.
polishing:
Diamond sandpaper (grit size 5–1 μm) was used for grinding in stages.
Polish to surface roughness Ra<0.05μm, no scratches.
Avoid damaging the pores by over-polishing.
Cleaning: Ethanol or ultrasonic cleaning to remove contaminants.

5.1.2 Microscopic observation

Equipment: Optical microscope or scanning electron microscope (SEM), magnification 200–1500x, resolution < 0.5 μm.
Light source: bright field illumination, adjust contrast to distinguish:
Porosity: Black.
Unbound carbon: black.
η phase: grayish white.
WC/Co matrix: white/grey.
Observation area: Randomly select at least 5 fields of view (total area > 1 mm²) .
Record:
Type A pores: count the number or area of pores <10μm.
Type B pores: Count the number or area of pores with a size of 10–25 μm.
Type C defects: Distinguish between free carbon and η phase, record defect area >25μm.

5.1.3 Data Analysis

Manual analysis: Count the number of pores/defects through the microscope eyepiece grid and calculate the volume fraction or number/unit area.
Image analysis: Use image analysis software to calculate the pore/defect area ratio (accuracy ± 0.01%).
Grading: Grades are determined based on A1–A5, B1–B5, and C1–C5.

5.2 Density measurement

Principle: The Archimedean method measures the sample density and compares it with the theoretical density (12–15.6 g/cm³ for WC-Co) to estimate the porosity.
step:
Measure the sample dry weight (accuracy ± 0.001 g) and weight in water.
Density = dry weight/(dry weight - weight in water) × liquid density.
Porosity = (theoretical density - measured density) / theoretical density × 100%.
Requirements: Accuracy: ±0.01 g/cm³ , repeat the measurement 3 times and take the average value.

5.3 Test conditions

Porosity error: <0.02%.
C-type defect error: <0.01%.
Environment: Temperature 23±2°C, humidity <60%, no vibration.
Operator: Metallographic analysis or density measurement training is required.

6. Acceptance requirements

6.1 Aviation cutting tools
Requirements: A1/B1/C1 (porosity <0.01%, no significant defects).

6.2 Mining picks
Requirements: A3/B3/C1 (porosity <0.2%, no C-type defects).

6.3 Wear-resistant parts
Requirements: A4/B4/C2 (porosity <0.6%, trace free carbon).

6.4 Military Parts
Requirements: A1/B1/C1 (porosity <0.01%, no significant defects).

7. Summary of key points of the standard

elements	content	Classification	Grading	Test Method	Acceptance requirements
Porosity	Type A (<10μm), Type B (10–25μm), Stomatal (10–100μm)	Type A Type B	A1–A5 (0–0.5%), B1–B5 (0–1.0%)	Metallographic microscope (200–1500x), image analysis accuracy ±0.01%; density measurement ±0.01 g/ cm³	Aviation tool: A1/B1; pick: A3/B3
Microscopic defects	Type C (unbound carbon or η phase, >25 μm)	Type C	C1–C5 (0–0.5%)	Metallographic observation, distinguishing between free carbon (black) and η phase (grayish white)	Aviation/Military: C1; Wear-resistant parts: C2
Testing requirements	Polished sample (Ra<0.05μm), observation area>1 mm²	Type A/B/C	Volume fraction or number of pores per unit area	Microscope resolution <0.5μm, environment 23±2°C	Porosity error <0.02%, C-type defect error <0.01%

appendix:

ISO 4505:1978

Microscopic evaluation of porosity and unbound carbon in cemented carbide

1. Scope of application

This standard specifies the microscopic evaluation method for porosity and uncombined carbon in cemented carbide, and is applicable to:

Tungsten carbide (WC) based cemented carbide, containing cobalt (Co), nickel (Ni) or iron (Fe) binder phase, can be added with titanium carbide (TiC), tantalum carbide (TaC), niobium carbide (NbC).

Cemented carbide produced by powder metallurgy process, including sintering, hot isostatic pressing (HIP) and coating products.

Applications such as cutting tools, mining picks, dies, wear parts, etc.

It is not suitable for non-WC-based cemented carbide or non-powder metallurgy materials.

2. Definitions

Cemented carbide: A composite material with WC as the main hard phase and Co/Ni/Fe as the bonding phase.

Porosity: The pores or air gaps inside a material, expressed as a volume fraction.

Unbound carbon: free carbon (C) or η phase caused by carbon deficiency (W3Co3C, W6Co6C).

Metallographic evaluation: Observe the polished surface of the sample under a microscope and count the distribution and content of pores and unbound carbon.

3. Classification of porosity and unbound carbon

3.1 Porosity

Type A pores:
Diameter <10μm, round or nearly round, evenly distributed.
Source: Particles are not densely packed and liquid phase sintering is insufficient.

Type B pores:
The diameter is 10–25 μm and the shape is irregular (e.g., elliptical, polygonal).
Source: uneven pressing and evaporation of lubricant residue.

Pores:
Diameter 10–100 μm, round or spherical, classified as type A/B.
Source: Gas capture during sintering (oxygen, nitrogen or volatiles).

3.2 Unbound carbon and η phase

Type C defects (unbound carbon):
Free carbon (C) particles, size > 25 µm, black and irregular.
Source: Excess carbon during sintering (C/W>1.02).

η phase:
Carbides - cobalt compounds (W_3Co_3C or W_6Co_6C), size > 25µm, off-white.
Source: Insufficient carbon during sintering (C/W<0.98).

4. Grading method

Porosity and unbound carbon are graded by volume fraction or number of pores and are classified into three categories: A, B, and C, with each category ranging from 00 (no defects) to 08 (highest defect content).

4.1 Type A pores

Volume fraction: 0–0.2%, diameter <10 µm.
Grading:
A00: No visible pores (<0.01%).
A02: 0.02%.
A04: 0.05%.
A06: 0.1%.
A08：0.2%.
Assessment: Number of pores per square millimeter (<10µm) or area percentage.

4.2 Type B pores

Volume fraction: 0–0.2%, diameter 10–25 µm.
Grading:
B00: No visible pores (<0.01%).
B02：0.02%.
B04：0.05%.
B06：0.1%.
B08：0.2%.
Assessment: Number of pores per square millimeter (10–25 µm) or area percentage.

4.3 C-type defects (unbound carbon/η phase)

Volume fraction: 0–0.2%, size >25 µm.
Grading:
C00: No unbound carbon or η phase (<0.01%).

C02: 0.02%.
C04: 0.05%.
C06：0.1%.
C08：0.2%.
Assessment: Defect area ratio per square millimeter, distinguishing between free carbon (black) and η phase (grey white).

4.4 Grading requirements

Volume fraction: The pore/defect area is counted by metallographic microscope with an accuracy of ±0.01%.
Observation area: at least 1 mm² , 5 mm² recommended .
Pores: Counted as type A/B, spherical pores of 10–100 μm were recorded separately.

5. Test Methods

5.1 Sample preparation

Cutting: Cut the samples (size 10 × 10 mm) avoiding cracks.
Mounting: Fixing the sample with resin.
polishing:
Diamond sandpaper (grit size 5–1 μm) was used for grinding in stages.
Polish to surface roughness Ra<0.1μm without scratches.
Avoid damaging the pores by over-polishing.
Cleaning: Ethanol or ultrasonic cleaning to remove contaminants.

5.2 Microscopic observation

Equipment: Light microscope, magnification 100–1000x, resolution <0.5 μm.
Light source: bright field illumination, adjust contrast to distinguish:
Porosity: Black.
Unbound carbon: black.
η phase: grayish white.
WC/Co matrix: white/grey.
Observation area: Randomly select at least 5 fields of view (total area > 1 mm²) .
Record:
Type A pores: count the number or area of pores <10μm.
Type B pores: Count the number or area of pores with a size of 10–25 μm.
Type C defects: Distinguish between free carbon and η phase, record defect area >25μm.

5.3 Data Analysis

Manual analysis: Count the number of pores/defects through the microscope eyepiece grid and calculate the volume fraction.

Image analysis: Use image analysis software to calculate the pore/defect area ratio (accuracy ± 0.01%).

Grading: Grades are determined based on A00–A08, B00–B08, and C00–C08.

5.4 Test conditions

Porosity error: <0.02%.

C-type defect error: <0.01%.

Environment: Temperature 20±5°C, humidity <60%, no vibration.

Operator: Microscopic analysis training required.

6. Acceptance requirements

6.1 Cutting tools

Requirements: A02/B00/C00 (porosity <0.02%, no B-type pores and C-type defects).

6.2 Mining picks

Requirements: A04/B04/C00 (porosity <0.1%, no C-type defects).

6.3 Wear-resistant parts

Requirements: A06/B06/C02 (porosity <0.2%, trace free carbon).

6.4 Medical Knives

Requirements: A00/B00/C00 (porosity <0.01%, no defects).

7. Summary of key points of the standard

elements	Content (μm)	Classification	Grading	Test Method	Acceptance requirements
Porosity	Type A (<10), Type B (10–25), Stomatal (10–100)	Type A Type B	A00–A08 (0–0.2%), B00–B08 (0–0.2%)	Metallographic microscope (100–1000 times), image analysis (accuracy ±0.01%)	Tool: A02/B00; Pick: A04/B04; Medical: A00/B00
Unbound carbon/η phase	Type C (free carbon or η phase, >25)	Type C	C00–C08 (0–0.2%)	Metallographic observation, distinguishing between free carbon (black) and η phase (grayish white)	Tool/cutting teeth: C00; wear parts: C02
Testing requirements	Polished sample (Ra<0.1), observation area>1 mm²	Type A/B/C	Volume fraction or number of pores per unit area	Microscope resolution <0.5μm, environment 20±5°C	Porosity error <0.02%, C-type defect error <0.01%

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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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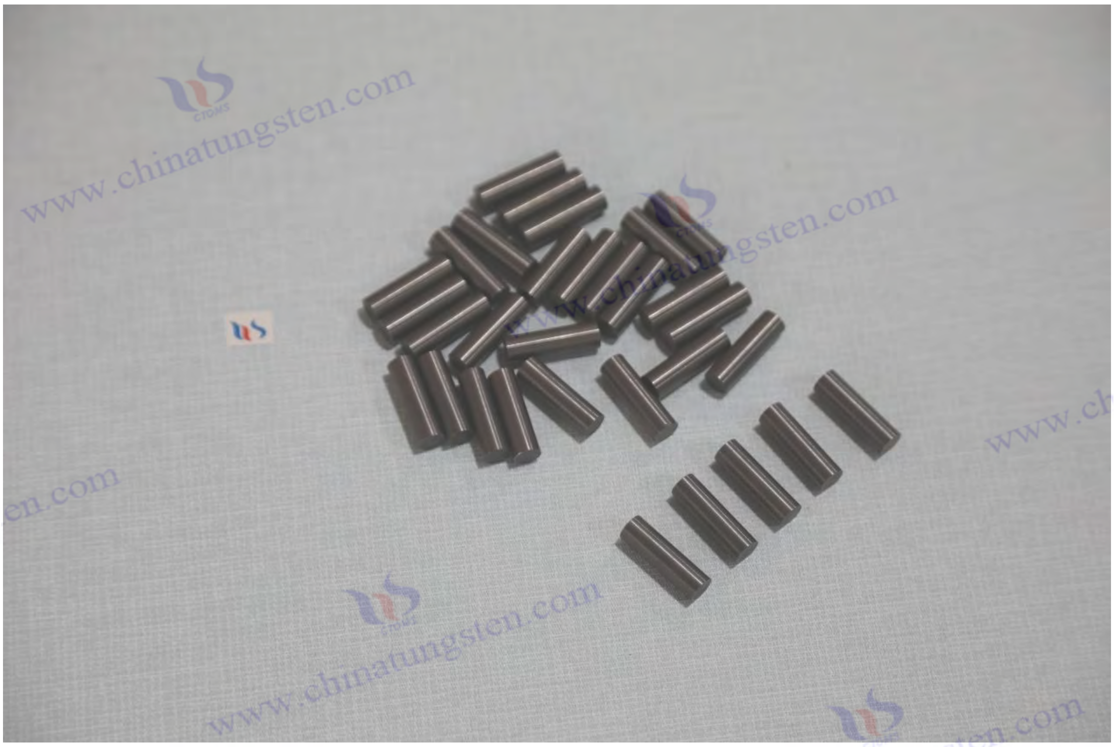

appendix:

Effects and comparison of cemented carbide auxiliary carbides (TiC , TaC , NbC)

1. Overview of cemented carbide and auxiliary carbides

Cemented Carbide is a composite material with tungsten carbide (WC) as the main hard phase and cobalt (Co) or nickel (Ni) as the binder phase. It is made by powder metallurgy process. It has high hardness (HV1000-1800) and excellent wear resistance. It is widely used in cutting tools, mining picks and wear-resistant parts. In order to optimize performance, cemented carbide is often added with auxiliary carbides, such as titanium carbide (TiC), tantalum carbide (TaC) and niobium carbide (NbC), and the content is usually 5-20% (mass fraction). These auxiliary carbides expand the application range of cemented carbide by improving hardness, wear resistance, red hardness and oxidation resistance.

The role of auxiliary carbides depends on their physical and chemical properties (such as hardness, melting point, crystal structure) and the synergistic effect with WC and the binder phase. TiC , TaC , and NbC are all cubic carbides with high hardness (HV2000-3000) and better thermal stability than WC (hexagonal system, HV1500-2000) . They improve the performance of cemented carbide through solid solution or particle strengthening mechanism. The following is a detailed analysis of the role of each auxiliary carbide and a comparison of their characteristics through a table.

2. The role of auxiliary carbides

2.1 Titanium Carbide (TiC)

The role of auxiliary carbides

Improve hardness

TiC has a higher hardness (HV2800–3200) than WC. Adding 5–15% can increase the hardness of cemented carbide to HV1400–1600, making it suitable for machining high-hardness materials (such as hardened steel, HV600–800).

Enhanced wear resistance

TiC particles (1–5 μm) are small and uniform, reducing wear (10–20 mm^3 in ASTM G65 test) and extending tool life.

Improved antioxidant properties

TiC forms a TiO2 protective layer at high temperatures (>800°C), which delays oxidation wear and is suitable for high-speed cutting.

Reduce density: TiC density (4.9 g/cm^3) is much lower than WC (15.6 g/cm^3), which reduces the weight of cemented carbide (reduced by 10–15%) and is suitable for lightweight aerospace components.

Limitations of auxiliary carbides

Decreased toughness: When the TiC addition is >15%, the fracture toughness (K_{1c}) drops to 8–10 MPa·m ^(1/2), making it prone to brittle fracture .

Higher cost: TiC price is higher than WC, which increases production cost.

Applications: TiC is commonly used in high-speed cutting tools (such as Kennametal K313), wear-resistant coatings and aerospace components.

2.2 Tantalum Carbide (TaC)

The role of tantalum carbide (TaC)

Improve red hardness: TaC has a higher melting point (3880°C) than WC (2870°C). Adding 3-10% can keep the hardness of cemented carbide at 1000°C (HV1200-1400), making it suitable for high-temperature processing (such as stainless steel and nickel-based alloys).

Enhanced thermal shock resistance: TaC reduces the thermal expansion coefficient (6.3×10^{-6} /K vs. WC 5.2×10^{-6} /K), reduces thermal cracks, and is suitable for intermittent cutting.

Improved anti-adhesion: TaC has low surface energy, which reduces the adhesion of workpiece materials during cutting, reduces the friction coefficient (0.2–0.3), and improves surface quality.

Limitations of Tantalum Carbide (TaC)

Expensive: TaC is much more expensive than WC and TiC , which limits its large-scale application.

Limited hardness gain: TaC hardness (HV1800–2000) is lower than TiC , and the hardness increase is small (about 5–10%).

Application: TaC is mostly used in high-end cutting tools (such as Sandvik PVD coated inserts), aviation turbine blade processing and hot die forging.

2.3 Niobium carbide (NbC)

Role of Niobium Carbide (NbC)

Grain refinement: NbC (particle size 0.5–2μm) inhibits WC grain growth (controlled at 1–3μm), improves the strength of cemented carbide (tensile strength increased by 10–15%) and toughness ($K_{1}c$ increased to 12–15 MPa·m ^(1/2)).

Enhanced corrosion resistance: NbC forms a Nb2O5 protective layer in an acidic environment (pH 2–4), with a salt spray weight loss of <0.1 mg/cm^2 , making it suitable for chemical equipment and marine engineering.

Improved abrasive wear resistance: NbC forms a solid solution with WC, increasing the strength of the phase boundary and reducing the wear loss by 15–25 mm^3 (ASTM G65).

Limitations of Niobium Carbide (NbC)

Insufficient red hardness: Although NbC has a high melting point (3600°C), its oxidation accelerates at >900°C, limiting its high-temperature applications.

Scarce resources: Niobium ore reserves are limited (about 4.3 million tons worldwide, 70% in Brazil), and prices fluctuate.

Application: NbC is commonly used in mining picks, wear-resistant parts and corrosion-resistant molds (such as Zhuzhou Diamond YN8 grade).

2.4 Synergy

Add combination

TiC , TaC and NbC are often used in combination (such as TiC 5% + TaC 3% + NbC 2%) to synergistically improve hardness, wear resistance and red hardness. For example, Sandvik GC2030 inserts are added with TiC-TaC-NbC composite, with a hardness of HV1500 and a life extension of 30%.

Solid solution strengthening

TiC , TaC , NbC and WC form a (W,Ti,Ta,Nb)C solid solution, and lattice distortion enhances hardness and deformation resistance (yield strength increases by 20%).

Gradient structure

By controlling the distribution of TiC / TaC / NbC , a gradient cemented carbide with high surface hardness and high toughness in the middle is formed, and the impact resistance is improved by 25%.

3. Comparison of the performance of auxiliary carbides

The following table compares the performance and application of TiC , TaC and NbC in cemented carbide, based on standard test data such as ASTM G65 and ISO 513:

Auxiliary carbide	Hardness HV	Melting point	density (g/	Toughness (K_{IC} , MPa ·m	Abrasion resistance	Red hardness(°C)	Corrosion resistance (salt	Cost (USD/kg)	Typical Applications

		(°C)	cm^3)	^(1/2))	(ASTM G65, mm^3)		spray weight loss, mg/ cm^2)		
TiC	2800–3200	3160	4.9	8–10	10–20	≤900	0.2–0.3	30–50	High-speed cutting tools, aviation parts
Tc	1800–2000	3880	14.3	10–12	15–25	≤1000	0.1–0.2	100–150	High temperature tools, hot die forging
Nb	2000–2400	3600	7.8	12–15	15–25	≤900	<0.1	50–80	Mining picks, corrosion-resistant molds

illustrate:

Performance parameters: hardness (Vickers hardness HV), toughness (fracture toughness $K_1 c$), wear resistance (ASTM G65 wear loss), red hardness (high temperature hardness holding temperature), corrosion resistance (salt spray test weight loss).

Typical applications: Based on the characteristics of TiC , TaC and NbC , list the main industrial scenarios.

Data source: Reference Sandvik, Kennametal, Zhuzhou Diamond Technology White Paper, ASTM G65, ISO 513 test standards.

4. Advantages, Disadvantages and Selection Principles of Auxiliary Carbides

4.1 Summary of advantages and disadvantages

TiC

Advantages: Highest hardness, lowest density, suitable for lightweight and high-speed cutting, good oxidation resistance.

Disadvantages: lower toughness, higher cost than WC, and prone to brittle fracture due to high addition.

Tc

Advantages: Excellent red hardness, strong resistance to thermal shock and adhesion, suitable for high temperature and intermittent cutting.

Disadvantages: expensive, limited hardness gain, and application is limited by cost.

Nb

Advantages: refined grains, optimal corrosion resistance, good toughness and resistance to abrasive wear.

Disadvantages: insufficient red hardness, scarce niobium resources , and large price fluctuations.

4.2 Selection Principles

High-speed cutting (such as aviation aluminum alloy, hardened steel)

TiC is the first choice to improve hardness and oxidation resistance. Typical grades include K313 (TiC 10%).

High temperature processing (such as nickel-based alloys, hot die forging)

Choose TaC to optimize red hardness and thermal shock resistance. Typical grades include GC2030 (TaC 5%).

Mining or corrosion resistant environment (such as chemical molds)

NbC is preferred to enhance toughness and corrosion resistance. Typical grades include YN8 (NbC 3%).

Comprehensive performance

The combination of TiC-TaC-NbC balances hardness, toughness and red hardness, and is commonly found in high-end tools and wear-resistant parts.

Cost-sensitive scenarios

Control the addition amount of TaC and NbC (<5%), focus on TiC , and reduce the cost by 10-20%.

5. Market and future trends

Market Status

In 2025, the cemented carbide market will be worth about $18 billion, with auxiliary carbides accounting for 20–30% of the raw material cost. TiC is the most widely used (accounting for 60%), while TaC and NbC account for 15% and 10% respectively due to cost and resource limitations .

Future Trends

Nanocarbide

Nano-scale TiC / NbC (<0.5μm) increases the hardness to HV1600–1800 and the toughness by 20%, and is expected to account for 15% of the market in 2027.

Green Manufacturing

Recycle TiC / TaC / NbC (recycling rate > 80%), reduce costs by 15% and reduce carbon footprint by 25%.

Intelligent design

AI optimizes carbide ratios (error <2%) and improves tool performance by 30%. For example, Sandvik will launch AI-assisted tool design in 2024.

Emerging Applications

TiC / TaC / NbC in new energy (such as wind turbine blade processing), medical (dental drill bits) and deep-sea drilling (corrosion-resistant components) is growing by 10% per year.

6. Conclusion

TiC , TaC , and NbC in cemented carbide have significantly expanded the application range of materials by improving hardness, wear resistance, red hardness, oxidation resistance, and corrosion resistance. TiC is suitable for high-speed cutting due to its high hardness and low density, TaC is suitable for high-temperature processing due to its excellent red hardness and thermal shock resistance, and NbC is superior to mining and chemical industries due to its refined grains and corrosion resistance. Combined addition and solid solution strengthening further optimize performance, but a balance between cost and performance is required . In the future, nanocarbides, green manufacturing, and intelligent design will promote the application of auxiliary carbides in high-precision and sustainable industries. When selecting auxiliary carbides, TiC , TaC , and NbC should be reasonably matched according to processing conditions, environmental requirements, and cost constraints to achieve optimal performance.

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

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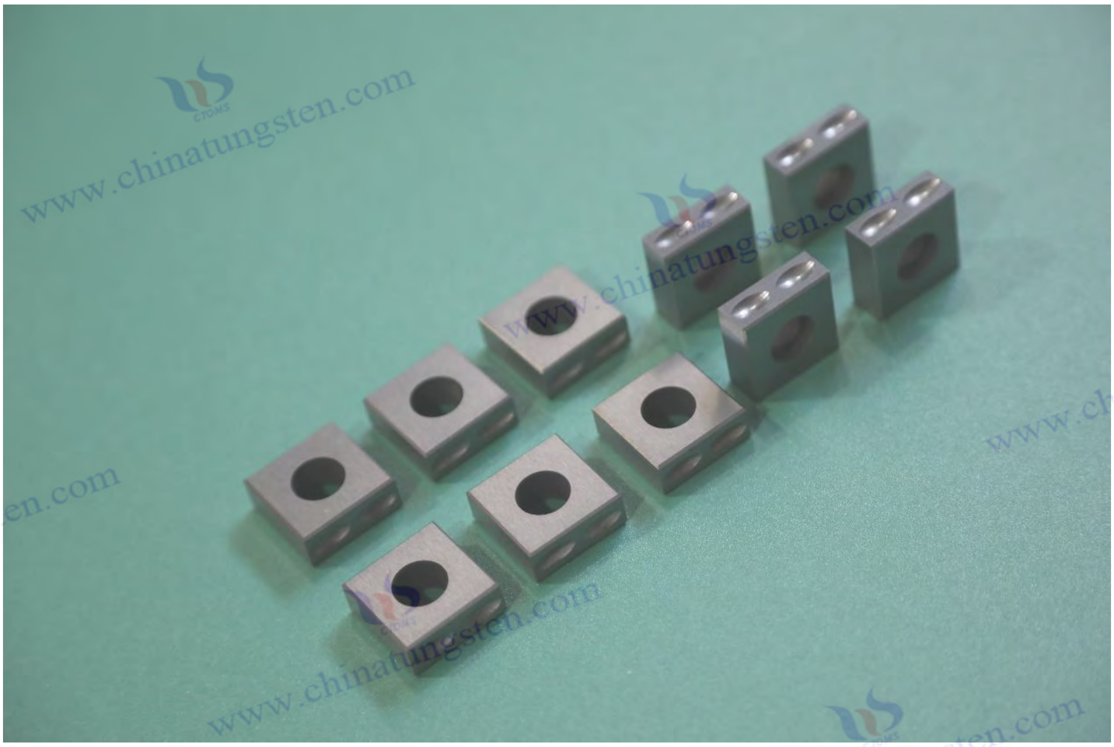

appendix:

Types and functions of cemented carbide binder phase

1. Overview

With its high hardness (14002200 HV), wear resistance and bending strength (1.52.5 GPa), cemented carbide has become the cornerstone of cutting tools, molds, and mining tools. Its performance comes from the synergy of hard phase (such as WC) and binder phase. The binder phase acts as a "binder" and "tuner", connecting the hard phase particles, giving toughness, corrosion resistance and processing properties. Since the invention of cemented carbide in Germany in 1923, the binder phase has expanded from single cobalt to nickel, iron, cobalt-nickel alloys , etc. In recent years, nano-binder phases, multi-element alloys (such as Co+Mo+Ni) and coating optimization have significantly improved performance. This article discusses the types, functions, microstructures, grade comparisons, coating interactions, optimization measures and applications of binder phases, combined with standards (such as GB/T 3849, ISO 4499).

2. Type of bonding phase

2.1 Cobalt (Co)

Features: more than 90%, content 620%, FCC structure, wetting angle <10°, melting point 1495°C.
Properties: Hardness 13001500 HV, KIC 812 MPa·m$^{1/2}$, flexural strength 22.5 GPa .
Applications: Cutting tools (YG6), moulds (YG15), mining (YG8).
Advantages and disadvantages: high toughness, porosity <0.01%, but corrosion rate 0.01 mm/year,

high cost ($3040/kg).

2.2 Nickel (Ni)

Features: corrosion resistance, content 515%, wetting angle ~15°, melting point 1455°C.
Performance: Corrosion rate <0.005 mm/year, hardness ~1350 HV, KIC 1012 MPa·m $^{1/2}$.
Applications: wet cutting tools, chemical molds, marine tools.
Advantages and disadvantages: strong corrosion resistance, low cost (US$1520/kg), slightly weak bonding strength.

2.3 Iron (Fe)

Features: low cost, content 510%, wetting angle ~20°, melting point 1538°C, easy to form η phase.
Performance: Hardness ~1300 HV, flexural strength 1.82.2 GPa , corrosion rate 0.02 mm/year.
Application: Low-cost mining tools.
Pros and Cons: 20% lower cost, 10% lower performance.

2.4 Cobalt-nickel alloy (Co+Ni)

Features: Combining the toughness of cobalt and the corrosion resistance of nickel , the content is 615%, and the ratio is adjustable.
Performance: Hardness 13501450 HV, Corrosion rate 0.007 mm/year, KIC 1012 MPa·m $^{1/2}$.
Application: aviation tools, chemical molds.
Advantages and disadvantages: Excellent overall performance, but the ratio needs to be optimized.

2.5 Others (Mo, Cu)

Features: Mo is heat-resistant (2623°C), Cu is corrosion-resistant (1085°C), and the content is <5%.
Performance: hardness 12001300 HV, flexural strength 1.52 GPa .
Application: high temperature tools (Mo), low load parts (Cu).
Progress: Co+Mo+Ni heat resistance increased by 20%, nano- cobalt toughness increased by 10%.

3. Adhesive phase effect

3.1 Bonding hard phase

Mechanism: Liquid phase sintering, wetting WC, binding energy ~2 J/ m² .
Effect: compressive strength 46 GPa , porosity <0.01%, energy saving 10%.

3.2 Improve toughness and strength

Mechanism: Plastic deformation, preventing crack propagation.

Effect: Cobalt increased from 6% to 15%, KIC increased by 50%, and flexural strength increased by 25%.

3.3 Adjusting hardness

Mechanism: The hardness of the bonding phase is low, and high content reduces the overall hardness.
Effect: 6% Co (1500 HV), 15% Co (1300 HV).

3.4 Improve corrosion resistance

Mechanism: Nickel forms a passivation layer.
Effect: Nickel-based corrosion rate <0.005 mm/year, 50% better than cobalt.

3.5 Improve processing performance

Mechanism: Liquid phase promotes densification.
Effect: Cobalt-based density >99.9%, shrinkage rate 1520%.

3.6 Interaction with Hard Phases

Mechanism: Cobalt WC binding energy ~2 J/m^2 , Cr3C2 inhibits grain growth.
Effect: Nano- cobalt toughness increased by 10%.

4. Microstructure of the bonding phase

4.1 Crystal structure

Cobalt: FCC (high ductility) + partial HCP (high hardness), fast cooling retains FCC, and toughness increases by 10%.
Nickel: stabilizes FCC, excellent corrosion resistance.
Iron: BCC, poor ductility, easy to form η phase.
SEM/TEM: Cobalt phase is reticular (0.52 µm), and nickel phase is relatively thin (0.31.5 µm).

4.2 Interface Features

Cobalt WC: Binding energy ~2 J/m^2 , flexural strength increased by 15%.
Nickel WC: Binding energy ~1.5 J/m^2 , strength reduced by 510%.
Iron WC: Easy to form η phase, strength reduced by 1015%.
Optimization: Cr3C2 increases bonding strength by 10%.

4.3 Distribution Characteristics

Uniform distribution: crack resistance increased by 20%.

Cobalt pool: strength reduced by 1015%.
SEM: YG6 uniformity >95%, YG15 cobalt pool 510%.
Optimization: ball milling + Cr3C2, uniformity increased by 15%.

4.4 Microscopic defects

Porosity: Porosity > 0.1% strength reduction by 20%.
η phase: hardness reduced by 510%.
Free carbon: strength reduced by 10%.
TEM : η phase needle-shaped (15 μm), free carbon cluster-shaped (0.52 μm).
Optimization: HIP strength increased by 15%.

5. Brand comparison

Brand	Adhesive Phase	content	Hardness (HV)	Flexural Strength (GPa)	Toughness (KIC)	Corrosion rate (mm/year)	application
YG6	cobalt	6%	1500	2.0	8	0.01	Cutting Tools
YG8	cobalt	8%	1450	2.2	9	0.01	Mining tools
YG15	cobalt	15%	1300	2.5	12	0.01	Stamping Die
YN10	nickel	10%	1350	2.0	10	<0.005	Wet cutting
YNC8	Co+Ni	8%	1400	2.3	11	0.007	Aviation tools
YF10	Iron + Cobalt	10%	1300	1.9	8	0.02	Low-cost tools

6. Interaction between binder phase and coating

6.1 Coating type

TiN : Hardness 20002500 HV, wear resistant.
CrN : Hardness 18002200 HV, corrosion resistant.
Al2O3: Hardness 2000 HV, heat resistance >1000°C.
Multilayer coating: TiN+Al2O3+TiCN, excellent comprehensive performance.

6.2 Interaction Mechanism

Interface bonding: Cobalt-based + TiN adhesion increases by 20%, and nickel-based + CrN life increases by 50%.
Thermal expansion matching: Cobalt + TiN increases stability by 15%.
Chemical stability: Nickel-based + CrN corrosion rate <0.003 mm/year.

6.3 Effect

Wear resistance: YG6+TiN increases life by 3 times .
Corrosion resistance: YN10+CrN doubles the service life .
Heat resistance: YNC8+Al2O3 cutting temperature>1000°C.

7. Optimization measures

Choice of binder phase: Cobalt (toughness), Nickel (corrosion resistance), Co+Ni (combined).
Controlled content: 6% cobalt (knives), 15% cobalt (molds).
Improved distribution: Cr3C2 toughness +5%.
Optimized sintering: HIP strength +15%.
Coating: CrN corrosion resistance +2 times .

8. Application Cases

YG6 tool: hardness 1500 HV, life 2 hours (+ TiN 6 hours).
YG15 mold: bending strength 2.5 GPa , life 120,000 times.
YN10 mold: corrosion rate <0.005 mm/year, life span 1 year (+ CrN 2 years).
YNC8 tool: hardness 1400 HV, life 3 hours (+Al2O3 4 hours).

9. Standards

GB/T 3849: Cobalt magnetic test.
ISO 4499: Microstructure.
ASTM B406: Flexural strength.
ASTM G31: Corrosion resistance.
ASTM C633: Coating Adhesion.

appendix:

Types and application selection of binders in cemented carbide mixing process

1. Overview

In the cemented carbide mixing process, the hard phase (WC), the binder phase (Co) and the additives are mixed by wet grinding or dry mixing , and a binder is added to prepare a uniform slurry for spray drying, granulation and pressing. The binder enhances particle bonding (green strength>5 MPa), improves fluidity (<30 s/50 g), controls particle morphology (D50 50200 μm), and decomposes before sintering (residual carbon <0.1%). Common binders include polyethylene glycol (PEG), polyvinyl alcohol (PVA), paraffin (PW), and rubber (SBR/BR). The selection needs to consider the slurry characteristics, process and application.

2. Types and characteristics of adhesives

2.1 Polyethylene glycol (PEG)

Chemical properties: HO(CH2CH2O) nH , molecular weight 200-20,000, soluble in water/ethanol, decomposition temperature 250-400°C, residual carbon <0.05%.
Physical properties: viscosity 100500 mPa·s , green strength 510 MPa, fluidity <25 s/50 g.
Advantages: good solubility, clean decomposition, low cost (1015 yuan/kg).
Disadvantages: Hygroscopic, slurry stability reduced by 10%.
Process: Add 12%, stir for 12 hours, decompose at 300-400°C.

2.2 Polyvinyl alcohol (PVA)

Chemical properties: (C2H4O)n, molecular weight 20,000-200,000, water soluble, decomposition temperature 200-350°C, residual carbon <0.1%.
Physical properties: viscosity 2001000 mPa·s , green strength 812 MPa, fluidity <28 s/50 g.
Advantages: High bonding strength, suitable for complex shapes.
Disadvantages: Ethanol solubility is poor, and drying cost increases by 1015%.
Process: Add 0.5-1.5%, stir for 23 hours, decompose at 250-350°C.

2.3 Paraffin wax (PW)

Chemical properties: hydrocarbons, molecular weight 3001000, melting point 5070°C, decomposition temperature 200500°C, residual carbon 0.10.2%.
Physical properties: viscosity 1050 mPa·s , green strength 48 MPa, fluidity <30 s/50 g.
Advantages: low cost (510 yuan/kg), good lubricity.
Disadvantages: much carbon residue, requiring organic solvent.
Process: Addition amount 23%, heating 6080°C, decomposition 400500°C.

2.4 Rubber (SBR/BR)

Chemical properties: molecular weight 50,000-500,000, decomposition temperature 300-600°C, residual carbon 0.2-0.3%.
Physical properties: viscosity 5002000 mPa·s , green strength 610 MPa, fluidity <30 s/50 g.
Advantages: High elasticity, crack resistance increased by 15%.
Disadvantages: much residual carbon and high cost (2030 yuan/kg).
Process: Addition amount 12%, heating 5070°C, decomposition 400600°C.

2.5 Others

PMMA: decomposition temperature 300-450°C, residual carbon <0.1%, suitable for high-precision tools.
CMC: decomposition temperature 250-350°C, residual carbon <0.05%, suitable for research and development.
Progress: Water-based nano binder, carbon residue <0.03%, fluidity increased by 15%.

3. Application Selection

3.1 Selection basis

Slurry: solid content 60-80%, ethanol is PEG/PW, water is PVA/CMC.
Process: PVA for wet pressing , PW for dry pressing .
Application: Choose PEG/PVA for cutting tools, SBR for molds, and PW for low cost.
Cost: PW (510 yuan/kg), PEG (1015 yuan/kg).

3.2 Applicable Scenarios

PEG: YG6/YG8 tool, D50 80150 μm , flowability <25 s/50 g.
PVA: Ultrafine grain tool, green strength 812 MPa.
PW: YG8 mining tools, cost reduced by 20%.
SBR: YG15 mold, crack resistance increased by 15%.
PMMA/CMC: R&D of aviation tools, D50 5080 μm .

3.3 Selection Process

Determine application and slurry characteristics.
Matching adhesive.
Verify fluidity, green strength, carbon residue.
Optimize the process.

4. Influencing factors

Content: 12% (PEG/PVA), 23% (PW/SBR).
Slurry: solid content 70%, viscosity 200 mPa·s .
Mixing: Stir at 500-1000 rpm for 12 hours.
Sintering: vacuum, 350400°C, carbon residue <0.1%.
Environment: humidity <40%, temperature 2030°C.

5. Optimization measures

Select binder: PEG/PVA (knife), SBR (mold).
Controlled content: Green strength 512 MPa.
Optimized slurry: solid content 7075%.
Improved mixing: Planetary ball milling , 15% more uniformity.
Optimized sintering: HIP, porosity <0.01%.

6. Application Cases

YG6 tool: 1.5% PEG, flowability 23 s/50 g, hardness 1500 HV.
Ultrafine -grained tool: 1% PVA, green strength 10 MPa, hardness 2000 HV.
YG8 mining tools: 2.5% PW, flexural strength 2.2 GPa .
YG15 mold: 1.5% SBR, life span 120,000 times.

7. Conclusion

Binders used in cemented carbide mixing include polyethylene glycol (PEG), polyvinyl alcohol (PVA), paraffin wax (PW), rubber (SBR/BR) and others (such as PMMA, CMC). PEG has good fluidity (<25 s/50 g) and is suitable for general-purpose tools; PVA has high green strength (812 MPa) and is suitable for ultrafine- grained tools; PW has low cost and is suitable for mining tools; SBR has strong crack resistance and is suitable for large molds. The selection needs to consider the slurry characteristics (solid content 6080%), process requirements, application scenarios and costs. Optimization measures can increase fluidity by 20%, green strength by 20%, hardness by 5%, and reduce costs by 20%. In the future, water-based nano-binders and dual binders will improve performance and environmental protection.

Cemented Carbide Binder Characteristics and Performance Comparison Table

Binder	Chemical properties	break down temperature ℃	Carbon residue %	green strength MPa	flow Sex s/50 g	cost Yuan/kg	advantage	shortcoming	Main Applications
PEG	HO(CH2CH2O) nH , molecular weight	250400	<0.05	510	<25	1015	Good fluidity, clean	Moisture absorption,	General tools (YG6, YG8), molds

	20020,000, water/ethanol soluble						decomposition, low cost	high molecular weight carbon residue	(YG15)
PVA	(C2H4O)n, molecular weight 20,000-200,000, water soluble	200350	<0.1	812	<28	1520	High bonding strength, suitable for complex shapes	Poor solubility in ethanol and high drying cost	Ultrafine grain cutting tools, complex molds
PW	Hydrocarbons, molecular weight 3001000, soluble in organic solvents	200500	0.10.2	48	<30	510	Low cost, good lubricity	A lot of residual carbon, need organic solvent	Mining tools (YG8), low cost molds
SBR/BR	Molecular weight 50,000-500,000, soluble in organic solvents	300600	0.20.3	610	<30	2030	High elasticity and strong crack resistance	Lots of carbon residue, high cost	Large molds (YG15), mining tools
PMMA	Molecular weight 50,000100,000, soluble in organic solvents	300450	<0.1	812	<28	~50	High precision, low carbon residue	High cost, poor solubility	High-precision tool development
CMC	Cellulose derivatives, water soluble	250350	<0.05	46	<25	2025	Good water solubility, low carbon residue	Green intensity low	Laboratory research and development, aviation tools

Decomposition temperature: affects the sintering process, <400°C is more suitable for vacuum sintering.
Carbon residue: <0.1% Ensure sintering porosity <0.1%.
Green strength: >5 MPa meets pressing requirements, 812 MPa is suitable for complex shapes.
Flowability: <30 s/50 g, in line with spray drying requirements (GB/T 1482).
Cost: PW is the most economical, PMMA is the highest.
Application selection: PEG/PVA for high performance, PW for low cost, SBR for large billets.

8. Standards

GB/T 3849: Cobalt magnetic test.   ISO 4499: Microstructure.
GB/T 1482: Fluidity.   ISO 3326:2013: Porosity.

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appendix:

Concept, Cause and Improvement of Decarburization and Carburization of Cemented Carbide

1. Overview

Cemented carbide is a composite material with tungsten carbide (WC) as the hard phase and cobalt (Co) or nickel (Ni) as the bonding phase. Its performance is highly dependent on the precise control of carbon content. The theoretical carbon content of WC is 6.13 wt %, and it needs to be controlled in the range of 6.08-6.18 wt % in actual production (Journal of the Chinese Society of Nonferrous Metals, 2024). Deviations in carbon content can lead to decarburization or carburization defects, which significantly affect the microstructure and properties of the material. Decarburization refers to insufficient carbon content, which causes WC to decompose or form brittle η phase (Co_3W_3C or Co_6W_6C), thereby reducing hardness and strength; carburization refers to excessive carbon content, which precipitates free carbon (graphite phase), affecting wear resistance and coating adhesion. This article combines Chinese national standards (GB/T 3849), international standards (ISO 4499) and industry data to analyze in detail the concepts, causes, effects and improvement measures of decarburization and carburization.

2. The concept of decarburization and carburization

2.1 Decarbonization

Decarbonization definition

The carbon content in cemented carbide is lower than the stoichiometric ratio of WC (6.13 wt %) , resulting in the decomposition of WC into W_2C or the formation of η phase (Co_3W_3C , Co_6W_6C) .

Microstructure

The η phase is needle-shaped or granular, with a size of 5-25 μm , a hardness of about HV 1800-2000, and a fracture toughness (KIC) of 4-6 MPa·m $^{1/2}$, which is much lower than the 8-15 MPa·m $^{1/2}$ of cemented carbide as a whole (Journal of Materials Science 2025). The brittleness of the η phase will lead to crack propagation and reduce the reliability of the material.

Decarbonization impact

Hardness decreases by 5%-10% (e.g. from HV 1800 to HV 1620-1710, ITIA 2024).

The flexural strength (TRS) decreases by 10%-15% (from 2200 MPa to 1870-1980 MPa, ASTM B406 test).

Corrosion resistance decreases, and the corrosion rate increases by 15%-20% (the corrosion rate in a salt spray environment increases from 0.05 mm/year to 0.06-0.07 mm/year, ASTM G31).

Example: Under high-speed cutting conditions (200 m/min), decarburization causes the wear resistance of cemented carbide tools to decrease, and the cutting life is shortened by about 20%-30% (Journal of the Chinese Society of Nonferrous Metals, 2024).

2.2 Carburizing

definition

The carbon content in cemented carbide is higher than the stoichiometric ratio, and free carbon (graphite phase) is precipitated

.

Free carbon is in the form of clusters or flakes, with a size of 0.5-3 μm , and extremely low hardness (<HV 100). It is mainly distributed in **the** cobalt phase or grain boundaries, increasing the porosity (The Chinese Journal of Nonferrous Metals, 2024).

Hardness decreases by 3%-5% (from HV 1800 to HV 1710-1740, ITIA 2024).

The flexural strength decreased by 8%-10% (from 2200 MPa to 1980-2020 MPa).

Free carbon increases the wetting angle (from 5° to 15°-25°), resulting in a 15%-20% decrease in coating adhesion (ASTM C633 test).

Example: In stamping die applications, carburization increases the surface roughness of cemented carbide dies (Ra from 0.2 μm to 0.3-0.4 μm), increases the coating peeling rate by about 15%, and reduces the die life by 10%-15% (Journal of Materials Science 2025).

3. Causes of decarburization and carburization

3.1 Decarbonization

Raw material factors:

Insufficient carbon content (<6.10 wt %), such as the carbon content in WC powder is lower than the theoretical value (6.13 wt %).

The raw materials contain high levels of oxides (such as WO_3 or CoO_3) (0.03%-0.1%), which react with carbon to produce CO/ CO_2 during sintering , consuming carbon (Journal of Materials Science, 2025).

The quality of carbon black is unstable and contains impurities (such as sulfur and oxygen) that result in a carbon loss of approximately 0.05%-0.1% (ITIA 2024).

Atmosphere factors:

The oxygen content in the sintering atmosphere is >0.1%, which leads to carbon oxidation to generate CO/CO_2 , and the decarburization rate increases by about 10%-15%.

the hydrogen (H_2) content is too high (>5%), it will react with carbon to form CH_4 , taking away the carbon element (ITIA 2024).

H_2O) content in the atmosphere is >0.05%, which reacts with carbon to produce CO and H_2 , further aggravating decarburization (The Chinese Journal of Nonferrous Metals, 2024).

Temperature factors:

Sintering temperature>1450°C, WC decomposes into W_2C or η phase (reaction: $2WC + Co \rightarrow Co_3W_3C + C$) .

Temperature fluctuations (±10°C) lead to local decarburization and an increase in the η phase formation rate by 10%-15% (The Chinese Journal of Nonferrous Metals 2024).

If the insulation time is too long (>2 hours), carbon volatilization increases and the decarbonization risk increases by about 8% (Journal of Materials Science 2025).

Mixing factors:

The mixing is uneven and the local carbon distribution deviation is >0.1 wt %, resulting in regional decarbonization.

The residual carbon rate of organic binders (such as paraffin PW or SBR) is >0.1%, and they are not completely decomposed in the early stage of sintering, affecting the carbon balance (ITIA 2024).

Mixing equipment (such as ball mills) is polluted (such as iron filings), introducing oxides and consuming about 0.02%-0.05% of carbon (The Chinese Journal of Nonferrous Metals, 2024).

3.2 Carburizing

Raw material factors:

The carbon content is too high (>6.15 wt %), such as excessive carbon black addition (>0.5 wt %).

The carbon black particles are not uniformly sized (>10 μm), resulting in local excess carbon (ITIA 2024).

The carbide (such as WC) particles in the raw material are too fine (<0.1 μm), with high surface activity and adsorption of excessive carbon (Journal of Materials Science 2025).

Atmosphere factors:

CH_4 content in the sintering atmosphere (>1%) leads to carbon deposition and increases the carburizing rate by about 10%-15%.

Insufficient vacuum ($>10^{-2}$ Pa) inhibits carbon volatilization and causes the remaining free carbon to precipitate (ITIA 2024).

When the carbon potential in the atmosphere is too high (e.g., carbon potential > 1.2), carbon atoms diffuse to the surface of the material and precipitate graphite phase (The Chinese Journal of Nonferrous Metals, 2024).

Temperature factors:

When the sintering temperature is <1350°C, the carbon reaction is incomplete and the remaining free carbon is precipitated.

Temperature fluctuations (±10°C) lead to local carburization, and the volume share of free carbon increases by 5%-10% (Journal of the Chinese Society of Nonferrous Metals, 2024).

If the cooling rate is too slow (<5°C/min), carbon will precipitate during the cooling process and the carburizing rate will increase by about 5% (Journal of Materials Science 2025).

Mixing factors:

The residual carbon rate of paraffin wax (PW) or SBR in the mixture is 0.15%-0.3%, and the carbon content increases after decomposition.

Insufficient mixing time (<10 hours) results in uneven carbon distribution and an increase in local carburization rate of about 8%-12% (ITIA 2024).

Carbon black agglomerates during the mixing process (agglomerated particles > 20 μm), resulting in local excess carbon (The Chinese Journal of Nonferrous Metals, 2024).

Microscopic mechanism:

During decarburization, the η phase reduces the WC-Co interface binding energy (from 1.2 J/m² to 0.8-1.0 J/ m²) and increases the tendency of crack propagation (Journal of Materials Science 2025).

During carburizing, free carbon increases the wetting angle (from 5° to 15°-25°), reduces the wettability of cobalt relative to WC, and affects the coating adhesion (ITIA 2024).

A small deviation in carbon content (±0.1 wt %) will cause the interfacial stress to increase by about 10%-15%, further aggravating micro-defects (The Chinese Journal of Nonferrous Metals 2024).

4. Effects of decarburization and carburization

4.1 Microstructure

Decarbonization:

The η phase destroys the WC-Co interface, the volume of the cobalt pool increases by 5%-10%, and the grains grow abnormally (from 0.5 μm to 1-2 μm).

Porosity increase 0.05%-0.1% (ISO 3326:2013).

An increase of about 10% in interfacial stress leads to a 15%-20% increase in the probability of microcrack initiation (Journal of Materials Science 2025).

carburization:

Free carbon accumulates at the grain boundaries, increasing the porosity by 0.1%-0.15%.

The cobalt phase is unevenly distributed, the local wettability decreases by 10%-15%, and the grain boundary strength decreases by about 5% (The Chinese Journal of Nonferrous Metals 2024).

Free carbon particles induce stress concentration and increase the tendency of pore formation by about 8% (ITIA 2024).

4.2 Performance

hardness:

Decarbonization: decrease by 5%-10% (from HV 1800 to HV 1620-1710).
Carburizing: decrease by 3%-5% (HV 1800 to HV 1710-1740).

strength:

Decarburization: Flexural strength decreases by 10%-15% (2200 MPa to 1870-1980 MPa).
Carburizing: decreased by 8%-10% (2200 MPa to 1980-2020 MPa).

toughness:

Decarburization: Fracture toughness (KIC) decreases by 20%-25% (from 10 MPa·m$^{1/2}$ to 7.5-8 MPa·m$^{1/2}$).
Carburizing: Slightly increased by 5%-8% (from 10 MPa·m$^{1/2}$ to 10.5-10.8 MPa·m$^{1/2}$).

Corrosion resistance:

Decarburization: Corrosion rate increases by 15%-20% (from 0.05 mm/year to 0.06-0.07 mm/year, ASTM G31).
Carburization: The corrosion rate increases by about 5% (0.05 mm/year to 0.0525 mm/year).

Coating Adhesion:

Carburizing: Adhesion decreases by 15%-20% (from 50 MPa to 40-42.5 MPa, ASTM C633).
Decarburization: Adhesion decreases by about 5% (50 MPa to 47.5 MPa).

Abrasion resistance:

Decarburization: Wear rate increases by 20%-25% (from 0.06 mm^3 / N · m to 0.072-0.075 mm^3 / N · m , ASTM G65).
Carburizing: Wear rate increases by 10%-15% (from 0.06 mm^3 / N · m to 0.066-0.069 mm^3 / N · m) .

4.3 Application

Knife:

Decarburization causes the wear resistance of the tool to decrease and the cutting life to be reduced by 20%-30%. For example, in high-speed cutting (200 m/min), the life is reduced from 2 hours to 1.4-1.6 hours (Journal of the Chinese Society of Nonferrous Metals, 2024).
Carburizing increases the coating peeling rate by 15%-20% and reduces its life by 10%-15% (Journal of Materials Science 2025).

Mould:

Decarburization causes the impact resistance of the mold to decrease and its life span to be reduced by 15%-20%. For example, the life of a stamping mold is reduced from 120,000 times to 96,000-102,000 times.
Carburizing increases the surface roughness of the mold (Ra increases from 0.2 μm to 0.3-0.4 μm) and reduces its service life by 10%-15% (Journal of Materials Science 2025).

Mining tools:

Decarbonization increases the risk of fracture by about 25%-30%, e.g. the life of a mining drill bit in granite drilling drops from 2000 m to 1400-1500 m (ITIA 2024).
Carburizing causes the wear resistance to decrease by about 10%-15% and the drill bit life to decrease by 10%-12% (Journal of the Chinese Society of Nonferrous Metals, 2024).

5. Improvement measures

5.1 Raw material control

The carbon content was strictly controlled at 6.10-6.15 wt % (±0.05 wt %), and high-purity WC powder (carbon content 6.12-6.14 wt %, oxide <0.02%) was used.
Adding grain inhibitors such as Cr_3C_2 (0.3 %-0.8%) or VC (0.1%-0.5%) inhibits the formation of η phase and reduces the volume proportion of η phase by 8%-12% (ITIA 2024) .
High-purity carbon black (purity > 99.9%) is used to reduce the interference of impurities (such as sulfur and oxygen) on the carbon content, and the carbon loss rate is controlled at 0.01%-0.03% (Journal of the Chinese Society of Nonferrous Metals, 2024).

5.2 Mixing Optimization

Using a planetary ball mill for mixing (12-18 hours, 300-500 r/min), the uniformity is improved by 10%-15%, and the carbon distribution deviation is <0.05 wt %.
Use low carbon residue binders, such as PEG or PVA (carbon residue rate <0.03%), to replace traditional paraffin wax (carbon residue rate 0.1%-0.2%).
Optimizing ball milling media (such as WC balls instead of steel balls) can reduce iron pollution and reduce carbon consumption by about 0.02% (Journal of Materials Science, 2025).
Adding dispersants (such as stearic acid, 0.1%-0.3%) can reduce carbon black agglomeration and improve uniformity by 5%-8% (The Chinese Journal of Nonferrous Metals, 2024).

5.3 Sintering optimization

Vacuum sintering is adopted (vacuum degree $<10^{-3}$ Pa), and the oxygen in the atmosphere is controlled to be <0.05%, H_2 <2%, and H_2O<0.03% to avoid carbon oxidation or volatilization.
The sintering temperature is controlled at 1380-1420°C (±5°C) and the holding time is 1-1.5 hours to avoid WC decomposition or free carbon precipitation.
The cooling rate is controlled at 5-10°C/min, reducing the risk of free carbon precipitation by about 5% (Journal of Materials Science 2025).
Hot isostatic pressing (HIP, 100-150 MPa, 1350-1400°C) eliminates porosity, with a porosity of <0.01% (ISO 3326:2013).
Using an atmosphere monitoring system (real-time detection of CO/CH_4 content) to ensure that the carbon potential is <1.0, the carburizing rate is reduced by about 10% (ITIA 2024).

5.4 Detection Feedback

cobalt magnetic test (GB/T 3849) is used to detect the carbon content deviation (±0.05 wt %) and accurately control the η phase and free carbon.
Combining X-ray diffraction (XRD) and scanning electron microscopy (SEM) to analyze the

microstructure, the η phase/free carbon detection rate increased by 15%-20%.

Energy dispersive spectroscopy (EDS) is used to analyze carbon distribution, with the deviation controlled at ±0.03 wt %, and the defect rate reduced by 10%-15% (The Chinese Journal of Nonferrous Metals, 2024).

Implement online infrared spectroscopy monitoring to detect the CO/CO_2 content in the sintering atmosphere and adjust the process in real time, reducing the defect rate by about 8% (ITIA 2024).

5.5 Surface treatment

The free carbon layer (thickness 0.01-0.03 mm) was removed by polishing, and the surface roughness Ra was <0.2 μm .

Using PVD TiN , TiAlN or CrN coating (thickness 2-5 μm), the coating adhesion is improved by 15%-20% (ASTM C633).

Plasma cleaning is used to remove residual carbon on the surface, and the coating adhesion is improved by about 10% (Journal of Materials Science 2025).

Low temperature nitriding treatment (500-600°C) increases the surface hardness by about 5% and the corrosion resistance by 10%-15% (ASTM G31).

Effect:

The volume proportion of η phase and free carbon is reduced by 10%-15%.

Hardness increased by 5%-8% (from HV 1710 to HV 1800-1850).

The flexural strength increased by 10%-15% (from 1980 MPa to 2200-2300 MPa).

Wear resistance is improved by 15%-20%, and tool and mold life is extended by 20%-30%.

6. Application Cases

Low Co cemented carbide tools (WC-6%Co): Through vacuum sintering (1400°C, vacuum degree 10^{-3} Pa) and adding 0.5% Cr_3C_2 , the η phase is reduced by 10%-12%, the hardness reaches HV 1850, and the life is increased from 1.5 hours to 1.8-2 hours when cutting medium carbon steel (200 m/min) (Journal of the Chinese Society of Nonferrous Metals, 2024).

High Co cemented carbide mold (WC-15%Co): Precisely controlled carbon content (6.12 wt %) and polished, free carbon is reduced by 10%-15%, bending strength reaches 2.4-2.5 GPa , and the life of stamping mold is increased from 100,000 times to 115,000-120,000 times (ITIA 2024).

Ni-based cemented carbide mold (WC-10%Ni): Using HIP (150 MPa, 1400°C) and CrN coating, the porosity is <0.01%, the corrosion rate is <0.005 mm/year, and the service life of marine engineering components is increased from 0.8 years to 1.1-1.2 years (Journal of Materials Science 2025).

Ultrafine -grained carbide tools (WC grain size 0.2 μm): Using nano - WC powder and coated with Al_2O_3 (3 μm) , the hardness reaches HV 1950-2000, and the life is increased from 3 hours to 3.8-4 hours when cutting high-temperature alloys (250 m/min) (Journal of the Chinese Society of

Nonferrous Metals, 2024).

7. Standards

GB/T 3849-2015: Test method for magnetic properties of cobalt in cemented carbide , detection of carbon content deviation.
ISO 4499-2:2020: Evaluation of the microstructure of cemented carbides, analysis of eta phase and free carbon.
ASTM B406-96(2021) : Test method for flexural strength of cemented carbide.
ASTM G31-21: Test method for corrosion resistance of metallic materials.
ASTM C633-13(2021): Test method for adhesion of coatings.
ISO 3326:2013: Method for determination of porosity in cemented carbides.
ASTM G65-00(2010): Dry sand /rubber wheel abrasion test, evaluating wear resistance.

CTIA GROUP LTD

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