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

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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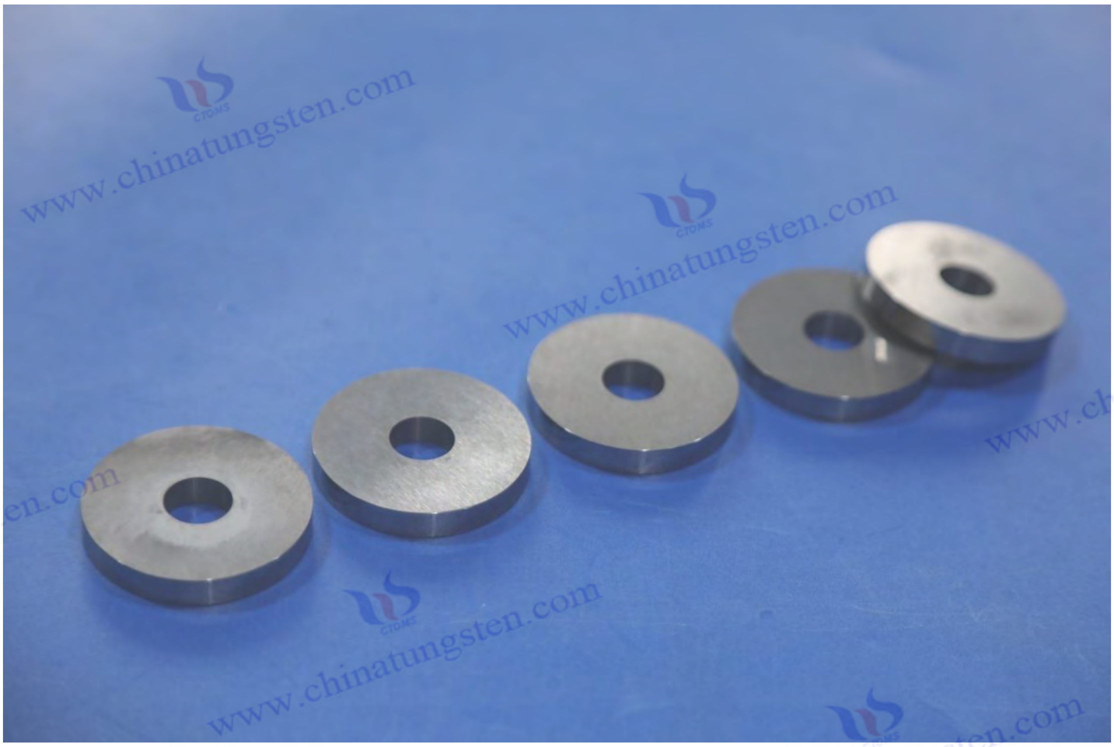

Part 2: Preparation Process of Cemented Carbide

Chapter 6: Coating and Composite Technology

Hard alloy (WCCo) plays an important role in aerospace, mining , energy and deep-sea engineering fields due to its excellent hardness (HV1500-2500±30), good toughness (K_{1c} 8-20 MPa·$m^{1/2}$ ± 0.5) and excellent compressive strength (>4000 MPa±100 MPa) . However, under extreme working conditions, high temperature (>1000°C±10°C), strong corrosion (pH<4±0.1) and high impact ($>10^3$Hz ± 100Hz) put forward higher requirements on surface performance, and single hard alloy is difficult to fully meet the requirements.

Coating and composite technology significantly enhances wear resistance (wear rate <0.06 mm^3/N·m ± 0.01 mm^3/N·m), corrosion resistance (corrosion rate <0.01 mm/year ± 0.002 mm / year) and thermal fatigue resistance (lifespan > 10^5 times ± 10^4 times) through surface modification (coating thickness 10-200μm±1μm) and structural optimization (gradient layer, nano WC <100 nm±5 nm) . These technologies not only extend the service life of cemented carbide, but also expand its application range, such as aviation turbine blades (lifespan > 5000 hours ± 500 hours), mining drill bits (> 1500 m ± 100 m) and deep-sea valves (> 5 years ± 0.5 years).

This chapter discusses the key processes and technical principles from four aspects: **cemented carbide coating preparation** , **coating materials, gradient and nanostructured cemented carbide and coating performance testing** . Coating preparation focuses on thermal spraying technology (such as HVOF, APS, detonation spraying), and achieves high hardness coating (HV 1200-1500±30) by optimizing spraying parameters (speed 600-4000 m/s±10 m/s, temperature 2000-

15000°C±100°C); material optimization covers WCCo , WCNiCr and multiphase coatings (such as WCTiCNi), balancing hardness and toughness (K_{1c} 10-15 MPa·$m^{1/2}$ ± 0.5); gradient and nanostructure improve comprehensive performance (strength>4500 MPa±100 MPa) through interface engineering and nanocrystal strengthening ; performance testing verifies coating reliability according to standards (such as ASTM G65, ISO 6508). Each section combines process details, scientific mechanisms, optimization strategies and engineering practices to reveal the core value of coating and composite technology.

For example, HVOF spraying WC12Co coating (speed 700 m/s±10 m/s, thickness 100μm±1μm) enables aviation turbine blades to maintain low wear (<0.05 mm^3/N·m±0.01 mm^3/N·m) in high-temperature airflow (1000°C±10°C) , with a service life of more than 5000 hours ± 500 hours; gradient WCCo (Co content 5%-15%±1%) improves the impact resistance of mining drill bits, with a drilling depth of 1800 m±100 m; nano WC coating (grain <100 nm±5 nm) is used for deep-sea valves, with corrosion resistance of more than 5 years±0.5 years. This chapter seamlessly connects with Chapter 5 (molding and sintering, WC particle size 0.1-10μm±0.01μm, density>99.5%±0.1%) through process parameters and performance data, laying the foundation for subsequent chapters (application and optimization).

6.1 Preparation of cemented carbide coating

Cemented carbide coatings are prepared by thermal spraying, physical/chemical vapor deposition (PVD/CVD) or laser cladding to deposit functional coatings (thickness 10-200μm±1μm, hardness HV 1200-1500±30) on high-performance substrates (hardness HV 1500-2500±30, surface roughness Ra<0.05μm±0.01μm). These coatings significantly improve wear resistance (wear rate <0.06 mm^3 / N · m ± 0.01 mm^3 / N · m) , corrosion resistance (corrosion rate <0.01 mm/year±0.002 mm/year) and high temperature oxidation resistance (oxidation weight gain <0.1 mg/cm^2 ± 0.02 mg/cm^2) , meeting the requirements of demanding working conditions. Thermal spraying technology is the preferred choice due to its high efficiency (deposition rate > 90% ± 2%), flexibility (applicable substrate size > 100 mm ± 1 mm) and economy (cost < \$500/m^2 ± \$ 50), and is widely used in the aviation, mining and energy fields.

This section discusses in detail the three mainstream technologies of high velocity oxygen fuel spraying (HVOF), plasma spraying (APS) and detonation spraying, and analyzes their process principles, parameter optimization and application scenarios. The coating quality depends on the spraying parameters (speed, temperature, spray distance), powder characteristics (particle size 10-50μm±1μm, fluidity 12-15 seconds/50g±0.5 seconds) and substrate pretreatment (roughness Ra 2-5μm±0.1μm). Through thermal fluid mechanics (jet velocity 600-4000 m/s±10 m/s) and interface bonding mechanism (bonding strength 50-80 MPa±5 MPa), this section reveals the core technology.

For example, HVOF sprayed WC12Co coating (porosity <1%±0.2%) is used for aviation turbine blades, with a wear life of more than 5000 hours±500 hours; APS sprayed WCNiCr coating (thickness 150μm±1μm) increases the life of mining drill bits to 1500 m±100 m. The following is a comprehensive guide for the preparation of high-performance coatings from the perspective of process details, influencing factors and engineering practice.

6.1.1 High velocity oxygen fuel spraying (HVOF, coating hardness HV 1200-1500)

Process Principle and Technology Overview

High velocity oxygen fuel spraying (HVOF) is a highly efficient thermal spraying technology that generates a high-temperature and high-speed jet through the combustion of oxygen and fuel to deposit powder materials on the cemented carbide substrate to form a high-hardness, wear-resistant coating. The core of HVOF is the supersonic jet (speed 600-800 m/s±10 m/s), which partially melts the powder particles (WCCo , particle size 10-45μm±1μm) and impacts the substrate at high speed to form a dense coating (porosity <1%±0.2%).

Compared with traditional spraying, HVOF has a lower temperature (2000-3000°C±50°C), effectively avoiding WC decomposition (<0.5%±0.1%), and is suitable for the preparation of high-performance cemented carbide coatings. HVOF equipment includes a spray gun (power>100 kW±10 kW), a combustion chamber (pressure 5-10 bar±0.5 bar) and a Laval nozzle (throat diameter 8-12 mm±0.1 mm). Oxygen (purity>99.5%±0.1%, flow rate 800-1200 L/min±10 L/min) reacts with fuel (such as kerosene, flow rate 0.3-0.5 L/min±0.01 L/min) in the combustion chamber , releasing high enthalpy (>10 MJ/kg±0.5 MJ/kg).

The jet is accelerated to supersonic speed through the Laval nozzle, driving the powder to hit the substrate (roughness Ra 2-5μm±0.1μm), forming flat splash particles (diameter 50-100μm±5μm), ensuring a bonding strength of 50-80 MPa±5 MPa. This process makes the coating hardness reach HV 1200-1500±30, which is widely used in aviation, mining and other fields.

Process parameters and deposition mechanism

HVOF coating formation involves four stages: combustion, particle acceleration, melting and deposition:

Combustion stage

Oxygen reacts with fuel to generate a high temperature jet (3000°C±50°C), the temperature is lower than the decomposition point of WC (~3500°C±50°C), reducing carbide loss (<0.5%±0.1%). The thermal enthalpy (>10 MJ/kg±0.5 MJ/kg) ensures that the particles are fully heated.

Particle Acceleration

The powder is accelerated in the jet (speed 700 m/s±10 m/s, residence time <1 ms±0.1 ms), the surface melts (melting rate 70%-90%±2%), the core remains solid (<50%±5% melted), and WC grains (0.5-2μm±0.01μm) are retained.

Particle melting and impact

The semi-molten particles impact the substrate to form flat spatter, and mechanical interlocking and trace diffusion (depth <1μm±0.1μm) form high bonding strength (>60 MPa±5 MPa).

Coating solidification

Rapid cooling (rate >10^6 K/s±10^5 K/s) results in a dense coating (porosity <1%±0.2%) with a hardness of HV 1400±30.

The jet dynamics follows the Bernoulli principle (velocity ~$\sqrt{(2\Delta P/\rho)}$, ρ~1 kg/m^3 ± 0.1 kg/m^3), and the thermal conductivity is 10^4 W/m^2 · K±10^3 W/m^2 · K. Optimizing the spray distance (250 mm±5 mm) and oxygen flow rate (1000 L/min±10 L/min) can reduce the porosity to <0.8%±0.1%. For example, the HVOF sprayed WC12Co (velocity 700 m/s±10 m/s, thickness 100μm±1μm) coating has a hardness of HV 1400±30 and a porosity of <0.8%±0.1%, which meets the high wear resistance requirements of aviation turbine blades.

Analysis of influencing factors

Coating performance is affected by many factors and needs to be precisely controlled:

Spraying speed

A dense coating (porosity <1%±0.2%) is formed at a speed of 700 m/s±10 m/s. Below 600 m/s±10 m/s, the particles have insufficient kinetic energy and the porosity increases to >2%±0.5%. Above 800 m/s±10 m/s, the particles are broken (<5μm±1μm) and the hardness decreases by 3%±0.5% (HV<1200±30).

Powder particle size

10-45μm±1μm ensures fluidity (12-15 seconds/50g±0.5 seconds) and melting rate (>80%±2%). Particle size <10μm±1μm is volatile (>5%±1%), porosity >1.5%±0.2%; >45μm±1μm is insufficiently melted (<60%±2%), and bonding strength drops to <40 MPa±5 MPa.

Spray distance

250 mm ± 5 mm equilibrium particle temperature (~2000°C ± 50°C). Spray distance < 200 mm ± 5 mm, overheating (> 3000°C ± 50°C) leading to WC decomposition (> 1% ± 0.2%); > 300 mm ± 5 mm, particle cooling (< 1500°C ± 50°C), bonding strength < 50 MPa ± 5 MPa.

Matrix roughness

Ra 2-5μm±0.1μm enhances mechanical interlocking (bonding strength>60 MPa±5 MPa). Roughness <1μm±0.1μm, bonding strength <40 MPa±5 MPa; >8μm±0.1μm induces stress concentration, crack rate>1%±0.2%.

Fuel flow rate

0.4 L/min±0.01 L/min provides stable energy (>10 MJ/kg±0.5 MJ/kg). Flow rate <0.3 L/min±0.01 L/min, porosity>2%±0.5%; >0.5 L/min±0.01 L/min, oxidation rate increases to>0.1%±0.02%.

The optimization strategy

is to obtain a coating with high hardness (HV 1400±30) and low porosity (<0.8%±0.1%). It is recommended to: use WC12Co powder with a particle size of 10-30μm±1μm to ensure high fluidity (12-15 seconds/50g±0.5 seconds) and melting rate (>80%±2%); control the spraying speed to 700 m/s±10 m/s and the spray distance to 250 mm±5 mm; control the substrate roughness to Ra 3μm±0.1μm to improve the bonding strength (>70 MPa±5 MPa); set the fuel flow rate to 0.4 L/min±0.01 L/min and the oxygen flow rate to 1000 L/min±10 L/min; adopt a closed-loop control system (temperature deviation <50°C±10°C) to improve process consistency (porosity deviation <0.1%±0.02%).

Engineering Application Practice

HVOF coating performs well in harsh environments:

Aviation turbine blades

The HVOF sprayed WC12Co coating (thickness 100μm±1μm, hardness HV 1400±30) has a wear rate of <0.05 mm^3/N · m ± 0.01 mm^3 / N · m and a service life of >5000 hours±500 hours in a high-temperature airflow of 1000°C±10°C (velocity>300 m/s±10 m/s), which is much longer than that of the uncoated substrate (<2000 hours±200 hours).

Mining drill bits

The HVOF sprayed WC10Co4Cr coating (porosity <0.8%±0.1%, bonding strength>70 MPa±5 MPa) has a service life of 1500 m±100 m in hard rock drilling (impact frequency>10^3 Hz ± 100 Hz), an increase of 50%±5%.

Deep sea valve

HVOF sprayed WCNiCr coating (thickness 150μm±1μm, hardness HV 1300±30) has a corrosion resistance life of >5 years±0.5 years in a seawater corrosion environment (pH 8±0.1, depth 5000 m±100 m), which is better than traditional coatings (<3±0.5 years).

6.1.2 Plasma spraying (APS) and detonation spraying

Process principle and technical overview

Plasma spraying (APS) and detonation spraying are high-energy thermal spraying technologies that drive powder deposition through plasma and detonation shock waves, respectively, and are suitable for surface modification of cemented carbide substrates (roughness Ra 2-5μm±0.1μm). APS uses a high-temperature plasma flow (>10000°C±100°C) to completely melt the powder to form a thicker coating (50-300μm±1μm); detonation spraying uses high-frequency explosion (5-10 Hz±0.1 Hz) to produce ultra-high-speed particles (2000-4000 m/s±10 m/s) to form a highly dense coating (porosity <0.5%±0.1%). APS is suitable for complex geometries (radius of curvature>5 mm±0.1 mm), and detonation spraying is known for its high bonding strength (>80 MPa±5 MPa), meeting the high reliability requirements of aviation and deep sea. The coating hardness ranges from HV 1000-1400±30, and the wear resistance and corrosion resistance are significantly improved.

For example, APS sprayed WC12Co coating (thickness 150μm±1μm) is used for mining drill bits, with a life of 1200 m±100 m; explosion sprayed WCNiCr coating (bonding strength>80 MPa±5 MPa) is used for aviation nozzles, with a wear life of>3000 hours±300 hours. This section discusses the technical characteristics from the perspective of process parameters, deposition mechanism and application scenarios.

Process parameters and deposition mechanism

Plasma spraying (APS)

APS uses a plasma gun (power 30-100 kW±5 kW) to generate a high-temperature plasma flow (temperature>10000°C±100°C, speed 800-1200 m/s±10 m/s), which completely melts the powder

(WCCo , particle size 15-50μm±1μm, fluidity 12-15 seconds/50g±0.5 seconds) (melting rate>95%±2%) and deposits it on the substrate. Parameters include: plasma gas (Ar / H_2 mixed gas, flow rate 50-80 L/min±1 L/min, Ar purity>99.99%±0.01%), spray distance (100-150 mm±5 mm), arc parameters (voltage 50-80 V±1 V, current 500-1000 A±10 A). The deposition mechanism is based on plasma dynamics (ion density 10^{22} m^{-3} ± 10^{21} m^{-3}). After the powder is completely melted, it hits the substrate to form a splash layer (thickness 5-10μm±0.1μm/layer). After cooling, the coating has a porosity of 1%-2%±0.2% and a bonding strength of 50-70 MPa±5 MPa. For example, the APS sprayed WC12Co coating (thickness 150μm±1μm) has a hardness of HV 1200±30 and a porosity of 1.5%±0.2%, which meets the wear resistance requirements of mining drill bits.

Detonation spraying

Detonation spraying uses a fuel-oxygen mixture (C_2H_2 / O_2 , ratio 2.5:1±0.1) to explode in a closed cavity (pressure>10MPa±0.5MPa, temperature~4000°C±50°C), driving the powder (WCNiCr , particle size 20-50μm±1μm) to impact the substrate at ultra-high speed (2000-4000 m/s±10 m / s). Parameters include: explosion frequency (5-10 Hz±0.1 Hz), spray distance (150-200 mm±5 mm), fuel ratio (C_2H_2 / O_2 2.5 : 1±0.1). The mechanism is based on the propagation of shock waves (speed>3000 m/s±10 m/s), partial melting of powder (melting rate 60%-80%±2%), and the formation of ultra-dense coatings (porosity <0.5%±0.1%, bonding strength>80 MPa±5 MPa). For example, the detonation sprayed WCNiCr coating (thickness 100μm±1μm) has a hardness of HV 1300±30 and a bonding strength of>80 MPa±5 MPa. It is used for aviation nozzles and has a wear life of>3000 hours±300 hours.

Analysis of influencing factors

Plasma spraying (APS)

Plasma power

50 kW±5 kW ensures complete melting of the powder (>95%±2%). Power <30 kW±5 kW, porosity >3%±0.5%; >100 kW±5 kW, substrate overheating (>500°C±10°C), crack rate >0.5%±0.1%.

Spray distance

120 mm ± 5 mm optimizes deposition efficiency (bonding strength > 60 MPa ± 5 MPa). Spray distance < 100 mm ± 5 mm, coating peeling rate > 1% ± 0.2%; > 150 mm ± 5 mm, porosity > 2% ± 0.2%.

Powder particle size

15-45μm±1μm balanced melting and deposition. Particle size <15μm±1μm, volatility >5%±1%; >45μm±1μm, hardness decreases by 2%±0.5% (HV<1100±30).

Substrate temperature

<200°C±10°C avoid stress concentration (<50 MPa±5 MPa); >300°C±10°C, crack rate>0.5%±0.1%.

Explosion spraying

Explosion frequency

8 Hz±0.1 Hz controls the coating thickness (10μm±0.1μm/time). When the frequency is >10 Hz±0.1 Hz, the crack rate is >0.5%±0.1%; when it is <5 Hz±0.1 Hz, the efficiency is reduced by 30%±5%.

Spray distance

180 mm ± 5 mm ensures bonding strength (> 80 MPa ± 5 MPa). Spray distance < 150 mm ± 5 mm, substrate damage > 0.01 mm ± 0.002 mm ; > 200 mm ± 5 mm, bonding strength < 60 MPa ± 5 MPa.

Fuel ratio

C_2H_2/O_2 2.5:1±0.1 provides stable energy. Ratio deviation>0.2, oxidation rate>0.2%±0.02%.

Powder particle size

20-50μm±1μm optimized deposition. Particle size <20μm±1μm, volatility>3%±0.5%; >50μm±1μm, porosity>1%±0.2%.

Optimization strategy

APS

Select 50 kW±5 kW power, 120 mm±5 mm spray distance, 15-30μm±1μm powder, Ar /H_2 flow rate 60 L/min±1 L/min, substrate temperature <200°C±10°C, ensure porosity <1.5%±0.2%, and bonding strength >60 MPa±5 MPa.

Explosion spraying

180 mm±5 mm, C_2H_2 / O_2 ratio to 2.5:1±0.1, powder to 20-40μm±1μm, porosity to <0.5%±0.1%, and bonding strength to >80 MPa±5 MPa.

General Optimization

The substrate roughness is Ra 3-5μm±0.1μm, and online monitoring is adopted (temperature deviation <50°C±10°C) to improve stability (performance deviation <1%±0.2%).

Engineering application practice

Aviation Nozzle

The explosion sprayed WCNiCr coating (thickness 100μm±1μm, bonding strength>80 MPa±5 MPa) has a wear resistance life of>3000 hours±300 hours in a high-temperature airflow of 800°C±10°C, which is better than that of traditional coatings (<1500 hours±200 hours).

Mining drill bits

APS sprayed WC12Co coating (hardness HV 1200±30, porosity <1.5%±0.2%) has a service life of 1200 m±100 m in hard rock drilling, an increase of 40%±5%.

Wear-resistant mold

APS sprayed WC10Co4Cr coating (thickness 200μm±1μm) maintained low wear (<0.07 mm^3 / N · m ± 0.01 mm^3 / N · m) during high frequency extrusion (>10^6 times±10^5 times) .

Deep sea valve

The explosion sprayed WCNiCr coating (porosity <0.5%±0.1%) has a service life of >5 years±0.5 years in seawater corrosion (pH 8±0.1).

6.2 Coating materials

Coating materials are the key to improving the performance of cemented carbide. By optimizing the composition and structure of the hard phase (WC, TiC) and the binder phase (Co, NiCr , Ni), high hardness (HV 1200-1500±30), excellent toughness (K_1c 10-15 MPa·$m^{1/2}$ ± 0.5) and excellent corrosion resistance (corrosion rate <0.01 mm/year±0.002 mm/year) can be achieved. It is necessary to balance hardness and toughness, control interface energy (<1 J/m^2 ± 0.1 J / m^2) and thermal expansion mismatch ($<5\times10^{-6}K^{-1}$ $\pm0.5\times10^{-6}K^{-1}$) , and adapt to complex working conditions in aviation, mining and deep sea. WCCo coating is known for its high hardness, WCNiCr coating improves corrosion resistance, and WCTiCNi multiphase coating takes into account hardness and toughness, broadening the application scenarios .

This section discusses strategies and engineering practices from two aspects: composition optimization of WCCo and WCNiCr coatings and multiphase composite coatings (WCTiCNi). Combining phase diagram analysis (WCCo liquidus 1320°C±5°C), diffusion kinetics (coefficient 10^{-10} cm^2 /s±10^{-11} cm^2 /s) and mechanical model (Orowan strengthening). For example, WC12Co coating (hardness HV 1300±30) is used for aviation turbine blades, with a wear rate of <0.05 mm^3 /N · m ± 0.01 mm^3 / N · m ; WC10Co4Cr coating (corrosion rate <0.01 mm/year±0.002 mm/year) is used for deep-sea valves; WCTiCNi coating (K_1c 12 MPa·$m^{1/2}$ ± 0.5) increases the life of mining drill bits to 1500 m±100 m.

6.2.1 Composition optimization of WCCo and WCNiCr coatings

Principle and technical overview

WCCo and WCNiCr coatings are the mainstream choices for cemented carbide surface modification. By adjusting the ratio of hard phase (WC, volume fraction 70%-90%±1%) and bonding phase (Co, NiCr , 10%-30%±1%), the performance is optimized to adapt to different working conditions. WCCo coating is known for its high hardness and wear resistance, and WCNiCr coating performs well in corrosive environments. The goal is to achieve a synergistic improvement in hardness (HV 1200-1500±30), toughness (K_1c 10-15 MPa·$m^{1/2}$ ± 0.5) and corrosion resistance, and ensure the bonding strength between the coating and the substrate (>60 MPa±5 MPa).

WCCo coating provides wear resistance with WC (hardness HV>2000±50, grain size 0.5-2μm±0.01μm), and Co (10%-20%±1%, toughness K_1c > 20 MPa·$m^{1/2}$ ± 0.5) to enhance interface bonding (interface energy <1 J/m^2 ± 0.1 J/m^2) . WCNiCr coating replaces Co with NiCr (Ni 8%-15%±1%, Cr 2%-5%±0.5%), and Cr forms a Cr_2O_3 passivation layer (thickness < 10 nm±1 nm), which significantly improves corrosion resistance (corrosion rate <0.01 mm/year±0.002 mm/year). Optimization is based on phase diagram (WCCo liquidus ~1320°C±5°C) and Orowan strengthening (grain spacing <1μm±0.01μm), supporting aviation and deep-sea applications.

Composition optimization and mechanism analysis

WCCo coating

depends on the ratio of WC and Co: WC hard phase (volume fraction 80%±1%, grain size 0.5-2μm±0.01μm) provides high hardness (HV>2000±50); Co binder phase (content 12%±1%) enhances interface bonding (>60 MPa±5 MPa) and improves toughness (K_1c 12 MPa $\cdot m^{1/2}$ ± 0.5). Too high Co (>20%±1%) reduces hardness (HV<1100±30), too low Co (<8%±1%) increases porosity (>2%±0.5%). The optimized WC12Co coating (HVOF spraying, speed 700 m/s±10 m/s) has a hardness of HV 1300±30, a porosity of <0.8%±0.1%, and a wear rate of <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m , which is suitable for aviation turbine blades (1000°C±10°C).

WCNiCr coating

WCNiCr coating improves corrosion resistance by replacing Co with NiCr : Ni base (8% -15 %±1%) provides toughness (K_1c >15MPa$\cdot m^{1/2}$ ± 0.5) and bonding strength (>50MPa±5MPa); Cr addition (4%±0.5%) forms a Cr_2O_3 passivation layer, anti-oxidation weight gain <0.05mg/cm^2±0.01mg/cm^2, and corrosion resistance is improved by 30%±5% (pH 4-10±0.1). WC10Co4Cr coating (HVOF, porosity <0.8%±0.1%) has a hardness of HV 1200±30 and a corrosion rate of <0.01mm/year ± 0.002mm / year . It is used for deep-sea valves with a service life of >5years±0.5years.

Analysis of influencing factors

WC particle size

0.5-2μm±0.01μm optimizes hardness (HV>1200±30). Particle size <0.5μm±0.01μm, decomposition rate>2%±0.5%; >2μm±0.01μm, toughness decreases by 3%±0.5%.

Binder phase content

Co 12%±1%, NiCr 12%±1% (Cr 4%±0.5%) Balanced performance. Co/ NiCr <8%±1%, porosity>2%±0.5%; >20%±1%, hardness decreases by 10%±2%.

Cr content

4%±0.5% enhances corrosion resistance; >6%±0.5% forms brittle Cr_3C_2 with a hardness of <1000±50.

Spraying process: HVOF (700 m/s±10 m/s) is better than APS, with porosity <1%±0.2% vs. >1.5%±0.2%.

Matrix temperature: <200°C±10°C to avoid stress (<50 MPa±5 MPa); >300°C±10°C, crack rate>0.5%±0.1%.

The optimization strategy

uses WC grains of 0.5-1μm±0.01μm, Co 12%±1% or NiCr 12%±1% (Cr 4%±0.5%); HVOF spraying (speed 700 m/s±10 m/s, spray distance 250 mm±5 mm) is used to reduce porosity (<0.8%±0.1%); substrate roughness Ra 3μm±0.1μm, preheating temperature 150°C±10°C, improve bonding strength (>70 MPa±5 MPa); adding 0.5%±0.01% VC inhibits WC decomposition (<0.5%±0.1%) and increases hardness by 3%±0.5%; and online monitoring is implemented (temperature deviation <50°C±10°C) to ensure consistency (performance deviation <1%±0.2%).

Engineering application practice

Aviation turbine blades
WC12Co coating (hardness HV 1300±30, wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m) , service life >5000 hours±500 hours.

Deep sea valve
WC10Co4Cr coating (corrosion rate <0.01 mm/year ± 0.002 mm/year), life span >5 years ± 0.5 years.

Mining drill bits
WC15Co coating (toughness $K_{1}c$ 12 MPa·m$^{1/2}$ ± 0.5), life>1500 m±100 m, improved by 50%±5%.

6.2.2 Multiphase composite coating (WCTiCNi)

Overview of the Principle and Technology of Multiphase Composite Coatings

The multiphase composite coating (WCTiCNi) introduces TiC (hardness HV>2500±50, volume fraction 5%-20%±1%) and Ni (8%-15%±1%) to improve the hardness (HV 1300-1500±30), toughness ($K_{1}c$ 10-15 MPa·m$^{1/2}$ ± 0.5) and wear resistance (wear rate <0.04 mm^3 /N · m ± 0.01 mm^3 / N · m) on the basis of WC-based coating (0.5-2μm±0.01μm). Compared with single WCCo coating, WCTiCNi coating has lower density (~10 g/cm^3 ± 0.1 g/cm^3 vs. 15 g/cm^3 ± 0.1 g/cm^3), stronger oxidation resistance (oxidation weight gain <0.05 mg/cm^2 ± 0.01 mg/cm^2), and is suitable for high impact and corrosive environments.

Performance is optimized through composite strengthening (TiC grain boundary pinning) and interface engineering (WC/ TiC interface energy <0.8 J/m^2 ± 0.1 J/ m^2). WC provides basic hardness, TiC reduces density and enhances oxidation resistance, and Ni improves toughness and corrosion resistance. For example, HVOF sprayed WC10TiC12Ni coating (TiC 10%±1%) has a hardness of HV 1400±30 and a porosity of <1%±0.2%, and is used in mining drill bits with a life of >1500 m±100 m.

Composition optimization and mechanism analysis of multiphase composite coatings

Performance depends on the proportion of each phase and microstructure
WC/ TiC hard phase (WC volume fraction 70%-85%±1%) provides hardness (HV>2000±50), TiC (10%±1%, density 4.9 g/cm^3 ± 0.1 g/cm^3) improves oxidation resistance (oxidation weight gain <0.05 mg/cm^2 ± 0.01 mg/cm^2) ; Ni binder phase (12%±1%) provides toughness ($K_{1}c$ > 15 MPa ·m$^{1/2}$ ± 0.5) and corrosion resistance (corrosion rate <0.01 mm/year±0.002 mm/year). Optimization is based on Orowan strengthening (grain spacing <1μm±0.01μm) and phase diagram analysis (WCTiCNi liquidus ~1350°C±5°C). WC10TiC12Ni coating (HVOF, porosity <1%±0.2%) has a hardness of HV 1400±30, a toughness of $K_{1}c$ 12 MPa·m$^{1/2}$ ± 0.5, and a wear rate of <0.04 mm^3 /N · m ± 0.01 mm^3 / N · m .

Analysis of influencing factors

TiC content

10%±1% balances hardness and toughness. >20%±1%, brittle phase is formed ($K_{1}c < 8$ MPa·m$^{1/2}$ ± 0.5); <5%±1%, insufficient hardness (HV<1200±30).

Ni content

12%±1% optimizes bonding strength (>60 MPa±5 MPa). >15%±1%, hardness decreases by 5%±1%; <8%±1%, porosity>2%±0.5%.

Particle size

WC/ TiC 0.5-1μm±0.01μm ensures uniformity (deviation <5%±1%). >2μm±0.01μm, toughness decreases by 3%±0.5%.

Spraying process

HVOF (700 m/s±10 m/s) controls TiC decomposition (<1%±0.2%); APS (>10000°C±100°C), decomposition rate>3%±0.5%.

Substrate preheating

150°C±10°C improves bonding strength (>70 MPa±5 MPa); >200°C±10°C, stress >50 MPa±5 MPa.

The optimization strategy

uses WC/ TiC grains of 0.5-1μm±0.01μm, TiC 10%±1%, and Ni 12%±1%; HVOF spraying (speed 700 m/s±10 m/s, spray distance 250 mm±5 mm) is used to control porosity (<1%±0.2%); substrate roughness Ra 3μm±0.1μm, preheating temperature 150°C±10°C; 0.3%±0.01% VC is added to inhibit TiC decomposition (<0.5%±0.1%) and increase hardness by 3%±0.5%; AI optimization parameters are implemented (deviation <1%±0.2%) to improve consistency.

Engineering application practice

Mining drill bits

WC10TiC12Ni coating (hardness HV 1400±30, wear rate <0.04 mm^3 / N · m ± 0.01 mm^3 / N · m) , life>1500 m±100 m, an increase of 50%±5%.

Wear-resistant mold

WC15TiC10Ni coating (toughness $K_{1}c$ 12 MPa·m$^{1/2}$ ± 0.5), life >10^6 times ±10^5 times.

Aviation Nozzle

WC10TiC12Ni coating (wear resistance <0.04 mm^3 / N · m ± 0.01 mm^3 / N · m) , service life >3000 hours ±300 hours.

6.3 Gradient and Nanostructured Cemented Carbides

Gradient and nanostructured cemented carbide significantly improves hardness (HV 2000-3000±50), toughness ($K_{1}c$ 10-20 MPa ·m$^{1/2}$ ± 0.5) and thermal fatigue resistance (lifespan > 10^5 times±10^4 times) through interface engineering (gradient WCCo , Co 0-20% ±1%) and nanocrystalline strengthening (WC<100 nm±5 nm). The gradient structure alleviates thermal expansion mismatch

($<5\times10^{-6}\ K^{-1} \pm 0.5\times10^{-6}\ K^{-1}$) through gradual composition change, and the nanostructure improves strength (>4500 MPa±100 MPa) through grain boundary strengthening (Hall-Petch effect, $\sigma_y \sim d^{-1/2}$), and performs well in aviation, mining and electronic manufacturing.

This section starts from the interface engineering of gradient WCCo and the preparation and challenges of nano WC (<100 nm), combining thermodynamics (interface energy <1 J/m² ± 0.1 J/m²), kinetics (agglomeration rate ~10^{-9} m/s±10^{-10} m/s) and mechanical model (Orowan strengthening) to explore the principles and practices. For example, gradient WCCo (Co 5%-15%±1%) is used for mining drill bits, and the impact life is >1800 m±100 m; nano WC coating (<100 nm±5 nm) is used for PCB drill bits, and the life is >10^5 holes±10^4 holes.

6.3.1 Interface engineering of gradient WCCo

Principle and technical overview

Gradient WCCo optimizes the interface stress (<50 MPa±5 MPa), improves the bonding strength (>80 MPa±5 MPa) and thermal fatigue resistance (>10^5 times±10^4 times) by gradually varying the Co content (0-20%±1%, gradient thickness 0.5-2 mm ±0.01 mm). Compared with uniform WCCo , the gradient structure alleviates thermal expansion mismatch (WC $4.5\times10^{-6}\ K^{-1} \pm 0.5\times10^{-6}\ K^{-1}$, Co $13\times10^{-6}\ K^{-1} \pm 0.5\times10^{-6}\ K^{-1}$), reduces interface cracks (<0.1%±0.02%), takes into account surface hardness (HV 1800±30) and internal toughness ($K_{1}c$ 15 MPa·m$^{1/2}$ ± 0.5), and is suitable for high impact environments.

The preparation method includes powder lamination and in-situ reaction. Powder lamination is to stack powders with different Co contents (5%-15%±1%) in layers.

Continuous gradients are formed by cold isostatic pressing (CIP, 250 MPa±5 MPa) and vacuum sintering (1450°C±10°C); in-situ reactions generate gradient layers by carbide diffusion (rate ~10^{-10} cm²/s±10^{-11} cm²/s). Stability is ensured based on interface thermodynamics (interface energy <1 J/m² ± 0.1 J/m²). For example, gradient WCCo (Co 5%-15%±1%) is used in mining drill bits with impact life >1800 m±100 m.

Preparation process and mechanism analysis

Powder preparation: Select WC (0.5-1μm±0.01μm) and Co (5%-15%±1%), and layered ratio (deviation <1%±0.2%).

Molding: CIP molding (250 MPa±5 MPa), green density>99%±0.1%.

Sintering: Vacuum sintering (1450°C±10°C, pressure <10^{-3} Pa±10^{-4} Pa), Co diffusion forming gradient (rate ~10^{-10} cm²/s±10^{-11} cm²/s).

Post-treatment: Heat treatment (600°C±10°C) to eliminate residual stress (<20 MPa±5 MPa).

The mechanism is based on thermal expansion mismatch mitigation and diffusion kinetics. The Co gradient (5%-15%±1%) makes the stress distribution uniform (<50 MPa±5 MPa), and the interface energy <1 J/m² ± 0.1 J/m² ensures the bonding strength (>80 MPa±5 MPa). For example, the gradient WCCo (layer thickness 1 mm±0.01 mm) has a hardness of HV 1800±30 and a toughness of K_1c 15 MPa·$m^{1/2}$ ± 0.5.

Analysis of influencing factors

% ±1% optimizes stress (<50 MPa±5 MPa). >20%±1%, toughness is too high (K_1c > 20 MPa·$m^{1/2}$ ± 0.5), hardness decreases by 5%±1%; <5%±1%, stress concentration (>100 MPa±5 MPa).
Layer thickness: 1 mm ± 0.01 mm to ensure continuity (deviation <1% ± 0.2%). <0.5 mm ± 0.01 mm, stress concentration (>100 MPa ± 5 MPa); >2 mm ± 0.01 mm, gradient blur (>5% ± 1%).
Sintering temperature: 1450°C±10°C controlled diffusion (>10^{-10} cm^2/s±10^{-11} cm^2/s). >1500°C±10°C, gradient fuzzy (>5%±1%); <1400°C±10°C, bonding strength <60 MPa±5 MPa.
Powder particle size: WC 0.5-1μm±0.01μm improves uniformity. >2μm±0.01μm, interface defects>1%±0.2%.
Additive: 0.5%±0.01% VC inhibits grain growth (<0.5μm±0.01μm) and increases hardness by 3%±0.5%.

The optimization strategy

selected a Co content of 5%-15%±1%, a layer thickness of 1 mm±0.01 mm, and a WC particle size of 0.5-1μm±0.01μm; a sintering temperature of 1450°C±10°C, and a pressure of <10^{-3} Pa ±10^{-4} Pa; adding 0.5%±0.01% VC to inhibit grain growth and increase hardness by 3%±0.5%; online monitoring (temperature deviation <10°C±2°C) to improve stability (performance deviation <1%±0.2%); post-processing heat treatment (600°C±10°C) to eliminate residual stress (<20 MPa±5 MPa).

Engineering application practice

Mining drill bits

Gradient WCCo (Co 5%-15%±1%, hardness HV 1800±30), in hard rock drilling (impact frequency>10^3 Hz ± 100 Hz), life>1800 m±100 m, an increase of 60%±5%.

Wear-resistant mold

Gradient WCCo (toughness K_1c 15 MPa ·$m^{1/2}$ ± 0.5), life span > 10^6times ± 10^5times .

Aviation tools

Gradient WCCo (stress <50 MPa±5 MPa), in high-speed cutting (>1000 m/min±10 m/min), has a life of >20 hours±1 hour, which is better than that of uniform structure (<10 hours±1 hour).

6.3.2 Preparation and Challenges of Nano-WC (<100 nm)

Principle and Technology OverviewNano

WC (grains <100 nm±5 nm) is prepared by high-energy ball milling, plasma synthesis or chemical vapor deposition (CVD), with a hardness of HV 2500-3000±50 and a strength of >5000 MPa±100 MPa, based on the Hall-Petch effect ($\sigma\_y \sim d^{-1/2}$, grain boundary density >10^{14} m^{-2} ± 10^{13} m^{-2}). Compared with traditional WC (0.5-2μm±0.01μm), nano WC grain boundary strengthening significantly improves strength and maintains toughness (K_{1c} 10-15 $MPa\cdot m^{1/2}$ ± 0.5). Nano-WC coatings (thickness 10-50μm±1μm) perform well in electronic manufacturing and deep-sea engineering, such as PCB drill bits (lifespan >10^5holes ± 10^4holes) .

challenges such as agglomeration (rate ~10^{-9} m/s±10^{-10} m/s), oxidation (O>0.1%±0.02%) and sintering grain growth (>200 nm±10 nm). The goal is to control the grain size (<100 nm±5 nm) and improve performance through process optimization and additives (VC, Cr_3C_2) .

Preparation process and mechanism analysis

High Energy Ball Milling

WC powder (initial particle size 1-10μm±0.01μm) was ground in a planetary mill (speed 300-500 rpm±10 rpm, ball-to-powder ratio 10:1±0.1) for 20-50 h±1 h, and the grain size was reduced to <100 nm±5 nm, with grain boundary strengthening contribution of ~500 MPa±50 MPa.

Plasma synthesis

WCl_6 reacts with CH_4 (flow rate 1:1±0.1) in plasma (>10000°C±100°C) to generate nano-WC (<80 nm±5 nm) with a deposition rate of >90%±2% .

CVD

$W(CO)_6$ reacts with H_2 (800-1000°C±10°C) to deposit a WC coating (grains <100 nm±5 nm, thickness 10-50μm±1μm).

The mechanism is based on grain boundary strengthening and agglomeration kinetics. The Hall-Petch effect increases the strength as the grain size decreases ($\sigma_y \sim d^{-1/2}$). The agglomeration rate (~10^{-9} m/s±10^{-10} m/s) is driven by the surface energy (~1 J/m^2 ± 0.1 J/m^2) and controlled by the addition of dispersant (PVA, 0.5%±0.01%). For example, the hardness of CVD nano-WC coating (<80 nm±5 nm) is HV 2500±50 and the toughness is K_{1c} 12 $MPa\cdot m^{1/2}$ ± 0.5.

Analysis of influencing factors

Grain size

<100 nm±5 nm requires high-energy grinding (>50 hours±1 hour). >100 nm±5 nm, hardness decreases by 10%±2%.

Reunion

Without dispersant, the agglomeration rate is >20%±2%; adding 0.5%±0.01% PVA, the agglomeration rate is <5%±1%.

Sintering temperature

<1200°C±10°C inhibits grain growth (<150 nm±10 nm); >1300°C±10°C, grain size is >200 nm±10 nm, and hardness decreases by 15%±2%.

atmosphere

Ar /H_2 (O_2 <10 ppm±1 ppm) avoid oxidation (O<0.05%±0.01%). O_2 >100 ppm±10 ppm, oxidation rate>0.2%±0.02%.

additive

0.3%±0.01% VC controls grain size (<100 nm±5 nm) and increases hardness by 5%±1%.

The optimization strategy

uses high-energy ball milling (50 hours ± 1 hour, rotation speed 400 rpm ± 10 rpm), grain size <100 nm ± 5 nm; sintering temperature <1200°C ± 10°C, Ar /H_2 atmosphere (O_2 < 10 ppm ± 1 ppm); adding 0.5% ± 0.01% PVA dispersant, agglomeration rate <5% ± 1%; adding 0.3% ± 0.01% VC to inhibit grain growth and increase hardness by 5% ± 1%; online particle size monitoring (deviation < 5 nm ± 1 nm) to ensure stability.

Engineering application practice

PCB Drill Bit

Nano WC coating (grain <80 nm±5 nm, hardness HV 2500±50), life>10^5 holes±10^4 holes, improved by 100%±10%.

Deep sea valve

Nano WC coating (corrosion rate <0.01 mm/year ± 0.002 mm/year), life span >5 years ± 0.5 years.

Aviation tools

Nano-WC coating (strength>5000 MPa±100 MPa) and lifespan>20 hours±1 hour are better than traditional coating (<10 hours±1 hour).

6.4 Coating performance test

The coating performance test adopts standardized methods (ASTM G65, ISO 6508, ASTM E384) to evaluate key indicators, including bonding strength (50-80 MPa±5 MPa), porosity (<1%±0.2%), hardness (HV 1200-1500±30), wear resistance (wear rate <0.06 mm^3 / N · m ± 0.01 mm^3 / N · m) and corrosion resistance (corrosion rate <0.01 mm/year±0.002 mm/year), ensuring that the coating meets the reliability requirements of aviation, mining and deep sea fields, while providing data for process optimization.

This section discusses the testing technology and practice from the perspectives of bonding strength, porosity and wear resistance, combining fracture mechanics (K_{1c} 10-15 MPa·$m^{1/2}$ ± 0.5), surface science (contact angle<10°±1°) and statistical analysis (error±0.01 mm^3 / N · m) . For example, HVOF WC12Co coating (bonding strength>70 MPa±5 MPa) is used for aviation turbine blades, with a life of>5000 hours±500 hours; nano WC coating (porosity<0.5%±0.1%) is used for PCB drill bits, with a life of> 10^5holes ± 10^4holes .

6.4.1 Bond strength (50-80 MPa) and porosity (<1%)

Test Principle and Technology Overview

Bonding strength and porosity are the core indicators for evaluating coating reliability, which directly affect the anti-stripping ability and durability. Bonding strength reflects the interfacial bonding force, and porosity measures the density. Standardized methods ensure the repeatability and comparability of results.

Bond strength (ASTM C633): Tensile test (rate 0.5 mm/min±0.01 mm/min) measures the separation force, strength 50-80 MPa±5 MPa. The specimen (diameter 25 mm±0.1 mm, coating thickness 100-200μm±1μm) is fixed with a high-strength adhesive (>100 MPa±5 MPa), and the calculation formula is $\sigma=F/A$.

Porosity (ASTM E2109): Scanning electron microscope (SEM, resolution <0.1μm±0.01μm) was used to analyze the cross section and measure the porosity ratio (<1%±0.2%). The specimen was polished to Ra<0.05μm±0.01μm and calculated based on the area ratio.

For example, HVOF WC12Co coating (bonding strength >70 MPa±5 MPa, porosity <0.8%±0.1%) is used for aviation turbine blades, and the anti-spalling life is >5000 hours±500 hours.

Test methods and mechanism analysis

Bonding strength

Based on fracture mechanics (K_{1c} 10-15 MPa ·$m^{1/2}$ ± 0.5), the interfacial bonding strength is determined by mechanical interlocking (Ra 2-5μm±0.1μm) and micro-diffusion (<1μm±0.1μm). The process includes sample preparation (thickness 100-200μm±1μm), fixation and stretching (rate 0.5 mm/min±0.01 mm/min). The HVOF coating (speed 700 m/s±10 m/s) has a bonding strength of >70 MPa±5 MPa , which is better than APS (<60 MPa±5 MPa).

Porosity

Based on SEM image analysis (magnification >1000×±100×), pores are shown as dark areas, and the area ratio is calculated by software. The HVOF porosity is <1%±0.2%, which is better than APS (~1.5%±0.2%).

Analysis of influencing factors

Bonding strength

Matrix roughness Ra 3-5μm±0.1μm improves strength (>70 MPa±5 MPa); <2μm±0.1μm, <50 MPa±5 MPa. Spraying speed 700 m/s±10 m/s is better than APS; preheating temperature 150°C±10°C enhances diffusion.

Porosity

Spraying power of 100 kW ± 10 kW (HVOF) is better than 50 kW ± 5 kW (APS); powder particle size of 10-30μm ± 1μm reduces porosity; spray distance optimizes density.

Optimization strategy

substrate roughness Ra 3-5μm±0.1μm, preheating temperature 150°C±10°C; HVOF (speed 700 m/s±10 m/s, power 100 kW±10 kW), powder 10-30μm±1μm; APS spray distance 120 mm±5 mm; explosion spray spray distance 180 mm±5 mm; high-precision SEM and stretching equipment to ensure accuracy.

Engineering application practice

Aviation turbine blades

HVOF WC12Co coating (bonding strength >70 MPa±5 MPa, porosity <0.8%±0.1%), life span >5000 hours±500 hours.

Deep sea valve

HVOF WC10Co4Cr coating (bonding strength >70 MPa±5 MPa), life span >5 years±0.5 years.

Mining drill bits

Explosion sprayed WCNiCr coating (bonding strength>80 MPa±5 MPa, porosity<0.5%±0.1%), life>1500 m±100 m.

6.4.2 Wear resistance (ASTM G65, wear rate $<0.06\ mm^3/N\cdot m$)

Test Principle and Technical Overview

Wear resistance is the core indicator for evaluating coating performance and directly affects the life of coatings in high friction environments. The ASTM G65 dry sand /rubber wheel test simulates abrasive wear and measures the wear rate ($<0.06\ mm^3/N\cdot m \pm 0.01\ mm^3/N\cdot m$), providing a basis for process optimization and material selection.

Testing Process

The specimen (50×25×10 mm±0.1 mm, thickness 100-200μm±1μm) was rubbed in a sand flow (SiO_2 , particle size 200-300μm±1μm, flow rate 300 g/min±10 g/min) (wheel speed 200 rpm±1 rpm, load 130 N±1 N, 6000 turns±10 turns). The wear volume was calculated by mass loss ($V=\Delta m/\rho$, $\rho=14\text{-}15\ g/cm^3 \pm 0.1\ g/cm^3$), and the wear rate=$V/(F\cdot S)$. For example, the HVOF WC12Co coating (wear rate $<0.05\ mm^3/N\cdot m \pm 0.01\ mm^3/N\cdot m$) has a life of >5000 hours±500 hours.

The test method and mechanism analysis

are based on the Archard model ($V=k\cdot F\cdot S/H$, $k=10^{-4}\pm10^{-5}$, H=HV 1200-1500±30). The higher the hardness and the lower the porosity, the stronger the wear resistance. The process includes preparing the sample, setting the parameters and calculating the wear rate. The wear rate of HVOF coating (hardness HV 1400±30) is $<0.05\ mm^3/N\cdot m \pm 0.01\ mm^3/N\cdot m$, which is better than APS ($>0.07\ mm^3/N\cdot m \pm 0.01\ mm^3/N\cdot m$).

Analysis of influencing factors

hardness

HV 1400±30 reduces wear rate ($<0.05\ mm^3/N\cdot m \pm 0.01\ mm^3/N\cdot m$) ; <1200±30, $>0.08\ mm^3/N\cdot m \pm 0.01\ mm^3/N\cdot m$.

Porosity

<1%±0.2% improves wear resistance; >2%±0.5%, wear rate increases by 20%±5%.

thickness

100-200μm±1μm balances wear resistance and stress.

Technology

HVOF is better than APS; WC particle size 0.5-1μm±0.01μm improves wear resistance.

The optimization strategy

uses HVOF (speed 700 m/s±10 m/s), WC grain size 0.5-1μm±0.01μm, thickness 100-200μm±1μm; adding 0.3%±0.01% VC or TiC (5%-10%±1%) to enhance hardness; online monitoring to ensure stability.

Engineering application practice

Aviation turbine blades: HVOF WC12Co coating, life>5000 hours ±500 hours.
Mining drill bit: WC10TiC12Ni coating, life span>1500m±100m.
PCB drill bit: Nano WC coating, life span >10^5 holes ±10^4 holes.

Summary and Outlook

Through process optimization, material design and structural innovation, coating and composite technology has made breakthroughs in wear resistance, corrosion resistance and thermal fatigue resistance of cemented carbide to meet the needs of various fields. In the future, it will promote the development of intelligent spraying, PVD/CVD composite coatings, green coatings and nano-composite coatings, and further improve performance and application scope.

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appendix:

What is cemented carbide coating

1. Definition

Hard alloy coating is a coating deposited on the surface of a substrate by a special process. Its main component is a composite material composed of a hard alloy material (such as carbide, nitride or boride) and a metal binder (such as cobalt or nickel). Hard alloy coatings usually use tungsten carbide (WC), titanium carbide (TiC) or chromium carbide (Cr3C2) as the main hard phase. They have extremely high hardness, wear resistance and corrosion resistance and are widely used to improve the surface properties of substrates.

2. Composition

Hard Phase:

Main ingredients: tungsten carbide (WC), titanium carbide (TiC), chromium carbide (Cr3C2), etc.
Features: High hardness (HV 1000-3000), high melting point (>2000°C), excellent wear resistance (Wear Resistance).

Binder Phase:

Common materials: cobalt (Co), nickel (Ni), iron (Fe) or their alloys.
Function: Bonds hard phase particles together to provide toughness (Toughness) and impact resistance (Impact Resistance).

Typical Ratio:

Hard phase: 70-90 wt % (weight percentage).
Binder phase: 10-30 wt %.
Example: In a WC-Co coating, WC accounts for 80-90% and Co accounts for 10-20%.

3. Preparation Methods

Cemented carbide coatings can be deposited on the substrate surface by a variety of processes, common methods include:

Thermal Spraying:
Methods:
High-Velocity Oxygen Fuel (HVOF) spraying: uses a high-velocity flame to spray powder onto the substrate surface.
Plasma Spraying: Powder is melted and deposited by a plasma arc.
Flame Spraying: Spraying using an oxy-acetylene flame.
Characteristics:
Coating thickness: 0.1-2 mm.
Bond Strength: 50-80 MPa.
Porosity: 1-5%.

Physical Vapor Deposition (PVD):
Methods:
Magnetron Sputtering.
Electron Beam Evaporation .
Characteristics:
Coating thickness: 1-10 μm .
Suitable for thin layers and smooth surfaces.
Chemical Vapor Deposition (CVD):
Methods:
A hard phase, such as a TiC or TiN coating, is deposited on the substrate surface by chemical reaction.
Characteristics:
Coating thickness: 5-20 μm .
High uniformity (High Uniformity), but requires high temperature (High Temperature, 700-1000°C).
Laser Cladding :
Methods:
The cemented carbide powder is melted using a laser beam and deposited on the substrate surface.
Characteristics:
Coating thickness: 0.5-3 mm.
High bond strength, close to metallurgical bonding.

4. Performance Characteristics

High Hardness:
Hardness range: HV 1000-3000 (Vickers hardness), or HRC 60-80 (Rockwell hardness).
Example: WC-Co coating hardness can reach HV 1200-1500.
Wear Resistance:
Hard phases (such as WC) can effectively resist abrasive wear and erosive wear.
Application: Prolong the service life of cutting tools and molds.
Corrosion Resistance:
The binder phase (such as Ni) can improve the corrosion resistance of the coating in acid and alkaline environments.
Example: Cr3C2-NiCr coating is suitable for high-temperature corrosion environment (High-Temperature Corrosion).
High-Temperature Resistance:
It can maintain performance at 600-1000°C and is suitable for high-temperature conditions.
Impact Resistance:
The binder phase provides a certain toughness, but the overall impact resistance is lower than that of pure metal materials.

5. Substrate Requirements

Material:
Common base materials: Steel, Cast Iron, Aluminum Alloy.
Requirements: The substrate must have certain strength and heat resistance.

Surface Preparation:
Cleaning: Remove oil and oxide layer.
Roughness: Ra 3.2-6.3 µm (Sandblasting).
Standard reference: ASME B46.1-2009 (surface roughness requirements).

6. Applications

Industrial Cutting Tools:
Example: WC-Co coating is used for milling cutters and drills to improve wear resistance and life.
Molds:
Example: Stamping Dies are coated with Cr3C2-NiCr to prevent wear and adhesion.
Aerospace:
Example: TiC coating is used for turbine blades to improve high temperature resistance and wear resistance.
Petrochemical:
Example: WC-Ni coatings are used on valves and drilling tools to resist erosion and corrosion.
Mining Equipment:
Example: WC-Co coating is used in rock drills to improve resistance to abrasive wear.

7. Testing Methods

Hardness Testing:
Method: Rockwell hardness (HRC, ISO 6508-1:2016), Vickers hardness (HV, ISO 6507-1:2018).
Example: WC-Co coating hardness test result is HRC 65 or HV 1200.
Microstructure Analysis:
Method: Scanning Electron Microscope (SEM).
Observation: Particle Distribution of Hard Phase, Porosity.
Bond Strength:
Method: Tensile Test, ASTM C633 standard.
Example: HVOF coating bond strength can reach 70 MPa.
Wear Resistance Test:
Method: ASTM G65 (Dry Sand /Rubber Wheel Abrasion Test).
Results: The wear rate of the WC-Co coating was lower than 0.01 mm^3 / N · m .
Surface Roughness:
Method: Stylus Profilometer, ASME B46.1-2009.
Example: Coating surface roughness Ra 0.8-2.0 µm .

8. Advantages and Disadvantages

Advantages:
High hardness and wear resistance significantly extend the service life of the substrate.
Corrosion resistance and high temperature resistance, suitable for harsh working conditions.
Customizable: Meet different needs by adjusting the ratio of hard phase and adhesive phase.
Disadvantages:
High Cost: For example, HVOF process equipment is expensive and material prices are high.

Brittleness: Cemented carbide coating has poor impact resistance and is prone to cracking.
Limited Thickness: Too thick a coating may cause peeling.

9. Typical Example

WC-Co coating:
Composition: WC 88 wt %, Co 12 wt %.
Process: HVOF spraying.
Performance: Hardness HV 1300, bonding strength 75 MPa, excellent wear resistance.
Application: Mining Drill Bits.

10. Trends

Nanostructured Coatings:
Nano-WC particles are used to improve hardness and toughness.
Example: Nano WC-Co coating can reach a hardness of HV 2000.
Multilayer Coatings:
Combining different cemented carbides (such as WC/ TiC) can improve overall performance.
Example: WC-Cr3C 2 multilayer coating is used for high temperature wear-resistant parts.
Eco-Friendly Processes:
Develop low-energy, low-emission deposition technologies such as Cold Spraying.

Summary

Cemented carbide coating is a high-performance surface protection technology, with carbide (such as WC) as the hard phase and metal (such as Co, Ni) as the bonding phase, which is deposited on the substrate surface through thermal spraying, PVD, CVD and other processes. It has high hardness, wear resistance and corrosion resistance and is widely used in industrial tools, molds, aerospace and other fields. Its main challenges are cost, brittleness and process complexity, but through nanotechnology and multi-layer structure design, the performance is expected to be further improved in the future.

appendix:

Cemented Carbide High Explosion Spraying (DGS) Technology

1. Definition of Detonation Gun Spraying (DGS)

Detonation Gun Spraying (DGS), also known as Detonation Gun Spraying, is a thermal spraying technology that generates high-temperature and high-pressure gas through periodic detonation reactions, accelerates cemented carbide powder (such as WC-Co) to supersonic speed (about 3500 m/s), and sprays it onto the surface of the substrate to form a high-hardness, wear-resistant coating. The technology was invented by HB Sargent et al. in 1955 and was originally named and commercialized by Union Carbide Company under the name " D- Gun" .

2. Principle of Detonation Gun Spraying (DGS) process

DGS uses a controlled detonation reaction to provide energy. The specific steps are as follows:

Detonation reaction

In the detonation gun (D-Gun), a mixed gas (such as oxygen O_2 and acetylene C_2H_2 , in a ratio of 1 :1-1.5:1) is ignited, and a detonation reaction occurs, generating a high temperature (about 4000°C) and high pressure (about 2-3 MPa) shock wave.

The shock wave speed can reach 3500 m/s, forming a supersonic airflow.

Powder acceleration and deposition

Cemented carbide powder (particle size 10-50 μm) is injected into the detonation gun, accelerated to supersonic speed (about 800-1200 m/s) by the shock wave, and partially melted or softened.

The powder particles hit the substrate surface at extremely high speed, undergo plastic deformation, cool rapidly and form a dense coating with a thickness of typically 50-300 μm .

Periodic Operation

After each detonation, the residual gas in the gun is purged with nitrogen (N_2) to prevent spontaneous combustion and flashback .

The spraying frequency is 1-10 Hz (1-10 detonations per second), depending on the coating thickness and material.

Substrate pretreatment

The substrate needs to be roughened by sandblasting (Ra 3-5 μm) and cleaned to remove oil and oxides to improve coating adhesion.

3. Characteristics of cemented carbide powder in Detonation Gun Spraying (DGS)

Commonly used materials:

WC-Co (cobalt content 6-17% wt): high hardness and wear resistance, commonly used in wear-resistant coatings.

Cr_3C_2 - NiCr : Resistant to high temperature oxidation, suitable for high temperature environment.
Oxide ceramics (such as Al_2O_3 - TiO_2) : used for special wear resistance or corrosion resistance requirements.

Powder requirements:
Particle size: 10-50 μm , to ensure spraying uniformity.
Purity: >99%, oxygen content <500 ppm, avoiding coating defects.
Morphology: spherical or nearly spherical, which is conducive to acceleration and deposition.

4. Application of Detonation Gun Spraying (DGS) in cemented carbide field

DGS technology is widely used in scenarios requiring high wear and corrosion resistance due to its high bonding strength and low porosity of the coating:

Aerospace:
Spraying aircraft engine parts (such as turbine blades, compressor blades) to enhance wear resistance and high temperature resistance.

Industrial Equipment:
Surface coating of cutting tools, dies, valves and pump bodies to extend service life.

Energy Industry:
Coatings for oil and gas drilling equipment (such as drill bits) to resist erosion and wear.
Specific example: Spraying WC-12Co coating on aircraft engine turbine blades can achieve a hardness of HV 1100-1300 and improve wear resistance by 5-8 times.

5. Process parameters of cemented carbide high explosion spraying (Detonation Gun Spraying , DGS)

Detonation gas: $O_2 + C_2H_2$ (ratio 1:1-1.5:1), or add a small amount of N_2 (5-10 %) to adjust the temperature.
Spraying frequency: 1-10 Hz, to control coating thickness.
Spraying distance: 150-200 mm, avoid overheating the substrate.
Powder feeding rate: 20-40 g/min, to ensure uniform coating.
Substrate temperature: controlled at <150°C to prevent heat affected zone (HAZ).
Purge gas: N_2 , purge for 2-3 seconds after each detonation.

6. Characteristics of Detonation Gun Spraying (DGS)

High temperature and high pressure: The detonation temperature is about 4000°C and the shock wave speed is 3500 m/s, which is much higher than other thermal spraying technologies.
Coating performance:
High hardness: WC-Co coating hardness HV 1100-1400.
Bonding strength: 70-100 MPa, mainly mechanical bonding, partial metallurgical bonding.
Very low porosity: <1%, dense coating.
Surface roughness: Ra 2-4 μm , less subsequent processing required.
Low heat input: substrate temperature <150°C, no heat affected zone (HAZ), no post heat treatment (PWHT) required.

Advantages and disadvantages of cemented carbide high explosion spraying (Detonation Gun Spraying , DGS)

Advantages:

High coating quality: porosity <1%, high bonding strength, excellent wear and corrosion resistance.

Low thermal impact: no thermal deformation of the substrate, suitable for precision parts.

Strong applicability: Can spray a variety of cemented carbides and ceramic materials (such as WC-Co, Al_2O_3).

Less post-processing: low surface roughness, reducing subsequent processing costs.

Disadvantages:

Complex equipment: The design of the blasting gun is complex and the cost is high (about 2-3 million yuan).

Operational risks: Involves detonation reaction, requiring strict safety measures (such as anti-flashback and nitrogen purging).

Low efficiency: periodic operation (1-10 Hz), slow spraying speed (about 0.1-0.3 m^2 / h).

Powder limitation: High strength powder (such as WC-Co) is required, otherwise it may break.

8. Comparison between Detonation Gun Spraying (DGS) and other thermal spraying technologies

Comparison with APS (plasma spray):

DGS: Lower porosity (<1% vs 2-5%), higher bond strength (70-100 MPa vs 30-70 MPa), but lower efficiency.

APS: Higher temperature (15,000°C), suitable for a wider range of materials, but more oxidation .

Compared with HVOF (High Velocity Oxygen Fuel Spray):

DGS: denser coating, higher hardness (HV 1100-1400 vs 800-1200), but more complex equipment.

HVOF: Faster spraying speed (0.5-1 m^2 / h), lower cost, less oxidation.

Compared with VPS (vacuum plasma spraying):

DGS: operates in the atmosphere, low cost, but may have trace oxidation.

VPS: No oxidation, lower porosity, but high equipment cost (about 5 million yuan).

Summarize

The cemented carbide high explosion spraying (DGS) technology uses a detonation reaction to supersonic spray cemented carbide powder onto the substrate to form a high-hardness, low-porosity coating, which is widely used in aerospace, industrial equipment and other fields. Its advantages are high coating quality and small thermal impact, but the equipment is complex and the efficiency is low. Process optimization (such as adjusting the detonation frequency and powder particle size) can further improve performance.

appendix:

Cemented Carbide Plasma Spraying (APS , Atmospheric Plasma Spraying) Technology

1. Definition of Atmospheric Plasma Spraying (APS)

Cemented carbide plasma spraying (**APS , Atmospheric Plasma Spraying**) is a thermal spraying technology that uses a plasma flame to heat cemented carbide powder (such as WC-Co, WC-Ni) to a molten or semi-molten state, and sprays it onto the substrate surface at high speed to form a dense cemented carbide coating. This process is carried out in an atmospheric environment, so it is called "atmospheric plasma spraying".

2. Principle of Atmospheric Plasma Spraying (APS)

The APS process is based on the high temperature and high energy characteristics of plasma. The main steps are as follows:

Plasma generation

Using a plasma spray gun, an inert gas (such as argon Ar) or a mixed gas (such as $Ar+H_2$) is introduced , and a high-frequency arc (voltage 50-100 V, current 500-1000 A) is used to ionize the gas to form a high-temperature plasma (temperature can reach 10,000-15,000°C).

Powder heating and acceleration

Cemented carbide powder (particle size 10-50 μm) is fed into the plasma flame through a powder feeder , rapidly heated to a molten or semi-molten state, and accelerated to 300-600 m/s.

Coating formation

The molten powder particles impact the substrate surface, cool rapidly and solidify to form a "splash" coating (splats), which are stacked to form a dense coating with a thickness of typically 50-500 μm .

Atmosphere Control

APS operates in an atmospheric environment and there is a certain risk of oxidation. Protective gas (such as Ar) is often used to partially shield the spray gun outlet to reduce coating oxidation.

3. Powder characteristics of cemented carbide plasma spraying (APS , Atmospheric Plasma Spraying)

Commonly used materials:

WC-Co (cobalt content 6-12% wt): high hardness and wear resistance, often used in wear-resistant coatings.

WC-Ni: Better corrosion resistance, suitable for acidic environment.

Cr_3C_2 - NiCr : Resistant to high temperature oxidation, suitable for high temperature environment.

Powder requirements:

Particle size: 10-50 μm , ensuring good fluidity and uniform melting.

Purity: >99%, impurities (such as O_2) <500 ppm, avoiding coating defects.

Morphology: spherical or nearly spherical, which is conducive to spraying uniformity.

4. Application of cemented carbide plasma spraying (APS , Atmospheric Plasma Spraying) in cemented carbide field

APS is widely used to prepare cemented carbide coatings on substrates (such as steel, stainless steel, aluminum, etc.) to improve wear resistance, corrosion resistance and high temperature resistance. The main applications include:

Industrial Parts:
Surface coating of cutting tools and molds can extend their service life.
Coatings for valves and pump bodies enhance resistance to wear and corrosion.
Aerospace:
Turbine blade coating, resistant to high temperature wear.
Energy Industry:
Coatings for boiler pipes and drilling equipment to resist erosion and high-temperature oxidation.
Specific example: Spraying WC-12Co coating on the surface of oil drill bit can achieve hardness of HRC 60-65 and improve wear resistance by 3-5 times.

5. Cemented Carbide Plasma Spraying (APS , Atmospheric Plasma Spraying) Process Parameters

Plasma gas: Ar (main gas, 30-50 L/min) + H_2 (auxiliary gas, 5-10 L/min).
Power: 30-50 kW (depending on the spray gun model).
Spraying distance: 80-150 mm, affects the density and bonding strength of the coating.
Powder feeding rate : 30-60 g/min, to ensure uniform coating.
Substrate pretreatment: sandblasting roughening (Ra 3-5 μm) to improve bonding strength.
Cooling: The substrate needs forced air cooling or water cooling, and the temperature should be controlled <200°C to avoid thermal stress.

6. Characteristics of cemented carbide plasma spraying (APS , Atmospheric Plasma Spraying)

High temperature capability: The plasma temperature is extremely high (10,000-15,000°C), capable of melting high melting point cemented carbides (such as WC, melting point 2870°C).
Coating performance:
High hardness: The hardness of WC-Co coating can reach HV 900-1200.
Bonding strength: 30-70 MPa (depending on substrate and process).
Porosity: 2-5%, dense but still has micropores.
Operating environment: carried out in the atmosphere, with simple equipment, suitable for industrial sites.

7. Advantages and disadvantages of cemented carbide plasma spraying (APS , Atmospheric Plasma Spraying)

Advantages:

Wide applicability: It can spray a variety of cemented carbide materials (such as WC-Co, Cr_3C_2-NiCr) to adapt to different substrates.

High efficiency: fast spraying speed (up to 0.5-1 m^2 / h), suitable for large area coating.

The coating has excellent performance: high hardness, good wear resistance, and significantly improves the life of parts.

The equipment cost is moderate: APS equipment (about 500,000 to 1,000,000 yuan) is cheaper than HVOF (high velocity oxygen fuel spray).

Disadvantages:

Oxidation risk: When operating in the atmosphere, the coating may be oxidized (such as WC decomposing into W_2C and generating oxide WO_3) , affecting performance.

Higher porosity: Porosity of 2-5% may reduce corrosion resistance and require post-processing (such as sealing).

Thermal influence: High temperature flame flow may cause thermal deformation of the substrate, and cooling must be strictly controlled.

Residual stress: Differences in thermal expansion coefficients between coating and substrate may lead to stress concentrations that affect bonding.

8. Comparison between cemented carbide plasma spraying (APS , Atmospheric Plasma Spraying) and other thermal spraying technologies

Compared with HVOF (High Velocity Oxygen Fuel Spray):

APS: Higher temperature (15,000°C), suitable for high melting point materials, but more oxidation and higher porosity (2-5%).

HVOF: lower temperature (3000°C), higher speed (>1000 m/s), less oxidation, lower porosity (<1%), but slightly lower hardness for WC-Co coatings (HV 800-1000).

Comparison with Vacuum Plasma Spray (VPS):

APS: In the atmosphere, the cost is low, but oxidation and porosity issues are significant.

VPS: Under vacuum, the coating quality is higher (porosity <1%, no oxidation), but the equipment is complex and the cost is high (2-5 million yuan).

Carbide plasma spraying (APS) uses high-temperature plasma to spray carbide powder onto the surface of the substrate to form a high-hardness, wear-resistant coating, which is widely used in industrial parts, aerospace and other fields. Its advantages are wide applicability and high efficiency, but attention should be paid to oxidation and porosity problems. Process optimization (such as adjusting the spraying distance and adding protective gas) can further improve the coating quality.

appendix:

High-velocity oxygen-fuel spraying technology for cemented carbide
(High-Velocity Oxygen Fuel Spraying , HVOF)

1. Definition of cemented carbide high velocity oxygen fuel spray (HVOF)

oxygen fuel spraying (HVOF) of cemented carbide is a thermal spraying technology that generates high temperature and high pressure airflow through high-speed combustion of fuel and oxygen, accelerates cemented carbide powder (such as WC-Co, Cr_3C_2 - NiCr) to supersonic speed (about 500-1000 m/s), sprays it onto the surface of the substrate, and forms a high hardness, low porosity wear-resistant coating. This technology was developed by Browning in the 1980s and is widely used due to its excellent coating performance.

2. Principle of cemented carbide high velocity oxygen fuel spraying (HVOF) process

HVOF technology uses high-speed airflow generated by fuel combustion. The main steps are as follows:

Combustion and airflow acceleration

In the gun combustion chamber, fuel (such as kerosene, propane or hydrogen) is mixed with oxygen and ignited at a combustion temperature of approximately 2800-3200°C.

The high-pressure combustion gas is accelerated to supersonic speed (500-1000 m/s) through the Laval Nozzle, forming a high-speed flame flow.

Powder heating and spraying

Cemented carbide powder (particle size 10-45 μm) is injected into the flame through a powder feeder , partially melted or softened (temperature below melting point, about 1000-1500°C), and accelerated to supersonic speed.

The powder particles impact the substrate with high kinetic energy, undergo plastic deformation, cool rapidly and deposit to form a dense coating with a thickness of typically 50-400 μm .

Atmosphere Control

The combustion is carried out in an oxygen-rich environment with a high flame velocity, which reduces the air entrainment and reduces the degree of coating oxidation.

Substrate pretreatment

The substrate needs to be sandblasted to roughen (Ra 3-5 μm) and cleaned to remove oil and oxides and improve bonding strength.

3. Characteristics of cemented carbide high velocity oxygen fuel spray (HVOF) powder

Commonly used materials:

WC-Co (cobalt content 6-17% wt): high hardness and wear resistance, commonly used in wear-resistant coatings.

Cr_3C_2 - NiCr : Resistant to high temperature oxidation and corrosion, suitable for high temperature environments.

NiCrBSi : Self-fluxing alloy, wear-resistant and corrosion-resistant.

Powder requirements:

Particle size: 10-45 μm , to ensure spraying uniformity.
Purity: >99%, oxygen content <500 ppm, avoiding coating defects.
Morphology: spherical or nearly spherical, which is conducive to acceleration and deposition.

4. Characteristics of cemented carbide high velocity oxygen fuel spraying (HVOF)

High speed low heat:
The flame velocity is as high as 500-1000 m/s, the particle kinetic energy is high, but the temperature is relatively low (1000-1500°C), which avoids the decomposition of cemented carbides (such as WC).
Coating properties:
High hardness: WC-Co coating hardness HV 800-1200.
Bonding strength: 50-80 MPa, mainly mechanical bonding, partial metallurgical bonding.
The porosity is extremely low: <1-2%, the coating is dense and has strong corrosion resistance.
Surface roughness: Ra 3-6 μm , can be optimized by polishing.
Low Oxidation:
The supersonic flame flow reduces air entrainment and the coating has a low oxide content (such as less decomposition of WC into W_2C or WO_3) .
Small influence of substrate:
The substrate temperature is <200°C, the heat affected zone (HAZ) is small, and no post-heat treatment is required.

5. High velocity oxygen fuel spray (HVOF) application of cemented carbide

HVOF is widely used in the field of cemented carbide, mainly to improve the wear resistance, corrosion resistance and high temperature resistance of the substrate:
Aerospace:
Aircraft landing gear and turbine blade coatings to enhance wear resistance and corrosion resistance.
Industrial Equipment:
Surface coating of cutting tools, dies, valves and pump bodies to extend service life.
Energy Industry:
Oil and gas drilling equipment (such as drill bits) and boiler pipe coatings to resist erosion and high-temperature oxidation.
Papermaking and printing:
Roller surface coating (such as WC-Co) improves wear resistance and surface quality.
Specific example:
Spraying WC-12Co coating on oil drill bits has a hardness of HV 1000-1200 and increases wear resistance by 4-6 times.
Cr_3C_2 - NiCr coating sprayed on the aircraft landing gear has a temperature resistance of up to 800°C and excellent corrosion resistance.

6. Advantages and disadvantages of cemented carbide high velocity oxygen fuel spraying (HVOF)

Advantages

High coating quality: porosity <1-2%, high bonding strength, excellent wear and corrosion resistance.

Low oxidation: high flame velocity, reducing oxidation, suitable for cemented carbide (such as WC-Co).

Small thermal impact: low substrate temperature, suitable for precision parts.

High efficiency: spraying speed 0.5-1 m² / h, suitable for industrial production.

Disadvantages

High equipment cost: HVOF equipment costs about RMB 1-2 million and is complex to maintain.

High powder requirements: high-strength powder (such as WC-Co) is required, otherwise it may break.

Loud noise: Supersonic flames produce high-decibel noise (>120 dB), requiring soundproofing facilities.

Thickness limit: When the coating thickness is >400 μm , it is easy to crack and needs to be sprayed in layers.

7. Comparison of cemented carbide high velocity oxygen fuel spraying (HVOF) and other thermal spraying technologies

Comparison with APS (plasma spraying)

HVOF: Lower porosity (<1-2% vs 2-5%), less oxidation, and higher bond strength (50-80 MPa vs 30-70 MPa).

APS: Higher temperature (15,000°C), suitable for a wider range of materials, but more oxidation .

Comparison with DGS (High Explosive Spraying)

HVOF: Higher efficiency (0.5-1 m² / h vs 0.1-0.3 m² / h) and lower equipment cost.

DGS: Higher coating hardness (HV 1100-1400 vs 800-1200), but more complicated to operate.

The cemented carbide HVOF (high velocity oxygen fuel spray) technology sprays cemented carbide powder onto the substrate through a supersonic flame flow to form a high hardness, low porosity coating with high coating quality, low oxidation, and low thermal impact. It is widely used in the aerospace, industrial equipment and energy industries. Process optimization (such as adjusting the fuel ratio and spraying distance) can further improve performance.

appendix:

Cemented Carbide Vacuum Plasma Spraying (VPS , Vacuum Plasma Spraying)

1. Definition of Cemented Carbide Vacuum Plasma Spraying (VPS)

Vacuum plasma spraying (VPS) of cemented carbide is a thermal spraying technology that uses plasma flame to heat cemented carbide powder (such as WC-Co, Cr_3C_2 - NiCr) to a molten or semi -molten state in a vacuum or low-pressure environment, and sprays it onto the surface of the substrate to form a high-hardness, low-porosity, non-oxidized wear-resistant coating. VPS technology was developed in the 1970s and is widely used in high-demand fields due to its extremely high coating quality.

2. Principle of Cemented Carbide Vacuum Plasma Spraying (VPS) Process

VPS technology is based on the characteristics of high temperature and vacuum environment of plasma. The main steps are as follows:

Vacuum environment:

Spraying is carried out in a vacuum chamber with a pressure controlled at 50-200 Pa (0.05-0.2 mbar), and the air is evacuated by a vacuum pump (mechanical pump + diffusion pump) to reduce oxygen and moisture.

Plasma Generation:

Using a plasma spray gun, an inert gas (such as argon Ar) or a mixed gas (such as $Ar+H_2$) is introduced , and the gas is ionized by a high-frequency arc (voltage 50-100 V, current 600-1200 A) to form a high-temperature plasma (temperature 10,000-15,000°C).

Powder heating and acceleration:

Cemented carbide powder (particle size 10-50 μm) is injected into the plasma flame through a powder feeder , rapidly heated to a molten or semi-molten state, and accelerated to 300-600 m/s.

Coating formation:

The molten particles hit the substrate surface, cool rapidly and solidify to form a "splash" coating (splats), which stacks to form a dense coating with a thickness of typically 50-500 μm .

Atmosphere Control:

The vacuum environment (<200 Pa) is almost oxygen-free, which prevents the coating from oxidizing (such as WC decomposing into W_2C or WO_3) .

3. Characteristics of cemented carbide vacuum plasma spraying (VPS) gold powder

Commonly used materials:

WC-Co (cobalt content 6-12% wt): high hardness and wear resistance, commonly used in wear-resistant coatings.

Cr_3C_2 - NiCr : Resistant to high temperature oxidation and corrosion, suitable for high temperature environments.

TiC -Ni: High hardness, suitable for special wear resistance requirements.

Powder requirements:

Particle size: 10-50 μm , to ensure spraying uniformity.
Purity: >99.5%, oxygen content <300 ppm, avoiding coating defects.
Morphology: Spherical or nearly spherical, which is conducive to acceleration and deposition.

4. Characteristics of cemented carbide vacuum plasma spraying (VPS)

No oxidation:
The vacuum environment (<200 Pa) eliminates oxidation, and the coating is free of oxides (such as WO_3), retaining the original properties of the cemented carbide.
Coating performance:
High hardness: WC-Co coating hardness HV 1000-1300.
Bonding strength: 60-90 MPa, partial metallurgical bonding, stronger bonding.
The porosity is extremely low: <0.5-1%, the coating is dense and has excellent corrosion resistance.
Surface roughness: Ra 2-4 μm , less subsequent processing required.
High temperature capability:
The plasma temperature is 10,000-15,000°C, which can melt high-melting-point cemented carbides (such as WC, melting point 2870°C).
Small influence of substrate:
The substrate temperature can be controlled at <200°C, and the heat affected zone (HAZ) is small, which is suitable for precision parts.
Complex process:
A vacuum chamber and vacuum system are required, which makes the operation complicated and the cost high.

5. Application of Vacuum Plasma Spraying (VPS) for Cemented Carbide

The application of VPS in the field of cemented carbide is mainly concentrated in high-performance and high-reliability scenarios:
Aerospace:
Turbine blades and combustion chamber coatings, resistant to high temperature wear and oxidation.
Coating for spacecraft components, resistant to corrosion in high temperature and vacuum environments.
Medical devices:
Surface coating of artificial joints (such as hip joints) to enhance wear resistance and biocompatibility.
Energy Industry:
Nuclear power equipment and gas turbine coatings to resist high temperature corrosion and wear.
High-end industry:
Precision molds and cutting tool coatings to extend service life.
Specific example:
Spraying WC-12Co coating on aviation turbine blades has a hardness of HV 1100-1300, wear resistance is improved by 5-10 times, and there is no oxide defect.
The Cr_3C_2 - NiCr coating is sprayed on nuclear power valves , which can withstand temperatures of 900°C and has excellent corrosion resistance.

6. Advantages and disadvantages of cemented carbide vacuum plasma spraying (VPS)

Advantages:

The coating quality is extremely high: porosity <0.5-1%, no oxidation, optimum wear and corrosion resistance.

High bonding strength: 60-90 MPa, partial metallurgical bonding, the coating is not easy to peel off.

Applicable to high-demand scenarios: suitable for high-performance fields such as aerospace, medical, etc.

Small thermal impact: low substrate temperature, suitable for precision parts.

Disadvantages:

High equipment cost: The VPS system (including the vacuum chamber) costs about RMB 3-5 million and is complex to maintain.

Low efficiency: vacuuming is required (each operation takes 30-60 minutes), spraying speed is about 0.3-0.5 m² / h.

Complex operation: The vacuum degree and atmosphere need to be strictly controlled, and the operator's technical skills are required to be high.

Limited substrate size: Due to the size of the vacuum chamber, spraying large parts is difficult.

7. Comparison between cemented carbide vacuum plasma spraying (VPS) and other thermal spraying technologies

Comparison with APS (plasma spray):

VPS: No oxidation, lower porosity (<0.5-1% vs 2-5%), higher bond strength (60-90 MPa vs 30-70 MPa).

APS : Operates in the atmosphere, has low cost, but is more oxidative.

Compared with HVOF (High Velocity Oxygen Fuel Spray):

VPS: The coating is denser and free of oxidation, but the cost is high and the efficiency is low.

HVOF: The porosity is slightly higher (<1-2%), but the equipment cost is low (1-2 million yuan) and the efficiency is high.

Compared with DGS (High Explosive Spraying):

VPS: No oxidation, suitable for higher demand scenarios, but lower efficiency.

DGS: Similar porosity (<1%), but may have trace oxidation, and slightly lower equipment cost (2-3 million yuan).

The cemented carbide vacuum plasma spraying (VPS) technology uses plasma to spray cemented carbide powder in a vacuum environment to form a high-hardness, non-oxidized, low-porosity coating. The characteristics include extremely high coating quality and low thermal impact. It is widely used in aerospace, medical and high-end industrial fields. However, its equipment cost is high and the efficiency is low, which is suitable for high-demand scenarios. Process optimization (such as adjusting the vacuum degree and spraying distance) can further improve performance.

Comparison table of cemented carbide spraying technologies

Technology Name	Plasma spraying (APS)	High explosive spraying (DGS)	High Velocity Oxygen-Fuel Spray (HVOF)	Vacuum Plasma Spraying (VPS)
definition	is sprayed with plasma flame in the atmosphere to form a wear-resistant coating.	The hard alloy is sprayed at supersonic speed through detonation reaction to form a high hardness coating.	The low porosity coating is formed by supersonic spraying of cemented carbide through the combustion of fuel and oxygen.	is sprayed with plasma flame in a vacuum environment to form an oxidation-free coating.
Process principle	Ar or Ar+ H_2 ionization, temperature 10,000-15,000°C. Powder (10-50 μm) is accelerated at 300-600 m/s. Atmospheric operation, Ar shielding.	$O_2+C_2H_2$ detonation, temperature 4000°C, shock wave 3500 m/s. Powder (10-50 μm) is accelerated at 800-1200 m/s. Frequency 1-10 Hz, N_2 purge .	O_2 + kerosene/propane combustion, temperature 2800-3200°C. Powder (10-45 μm) is accelerated at 500-1000 m/s. Laval nozzle.	Vacuum (50-200 Pa), Ar or Ar+H_2 ionization , temperature 10,000-15,000°C. Powder (10-50 μm) is accelerated at 300-600 m/s. Anaerobic environment.
Features	Strong high temperature capability, hardness HV 900-1200. Porosity 2-5%, bonding strength 30-70 MPa. Oxidation risk.	High temperature and high pressure, hardness HV 1100-1400. Porosity <1%, bonding strength 70-100 MPa. Low heat input.	High speed and low heat, hardness HV 800-1200. Porosity <1-2%, bonding strength 50-80 MPa. Low oxidation.	No oxidation, hardness HV 1000-1300. Porosity <0.5-1%, bonding strength 60-90 MPa. High temperature capability.
application	Cutting tools, valves, pump bodies. Turbine blades, boiler pipes. Example: Drill bit WC-12Co, wear resistance increased by 3-5 times.	Turbine blades, compressor blades. Cutting tools, oil and gas drill bits. Example: WC-12Co for turbine blades, wear resistance increased by 5-8 times.	Landing gear, turbine blades. Cutting tools, drilling equipment, rollers. Example: Drill bit WC-12Co, wear resistance increased by 4-6 times.	Turbine blades, spacecraft components. Medical joints, nuclear power equipment. Example: WC-12Co for turbine blades, wear resistance increased by 5-10 times.
Advantages and Disadvantages	Advantages: wide applicability, high efficiency (0.5-1 m^2 / h), moderate cost (500,000-1 million yuan). Disadvantages: high oxidation, porosity requires post-processing, thermal effects.	Advantages: high coating quality, low thermal impact, less post-processing. Disadvantages: complex equipment (2-3 million yuan), low efficiency (0.1-0.3 m^2 / h), high risk.	Advantages: high coating quality, low oxidation, high efficiency (0.5-1 m^2 / h). Disadvantages: high cost (1-2 million yuan), high noise, and limited thickness.	Advantages: Extremely high coating quality, no oxidation, suitable for high demands. Disadvantages: high cost (3-5 million yuan), low efficiency (0.3-0.5 m^2 / h), limited size.

appendix:

Carbide Interface Engineering

1. The connotation and significance of cemented carbide interface engineering

Cemented carbide (WC-Co), with tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase, is widely used in high-performance fields such as aviation nozzles, cutting tools, and electrolytic cell electrodes due to its excellent hardness (HV1000–1800), wear resistance, and high-temperature stability. However, its performance depends not only on the substrate material, but also on the interface characteristics (such as WC/Co interface, coating/substrate interface). The interface is a microscopic region between different phases (such as WC and Co, coating and substrate) inside or on the surface of the material, and its chemical composition, microstructure, and mechanical behavior directly affect the overall performance of the material. Under extreme conditions, such as high-temperature erosion (1000–1600°C) of aviation nozzles or highly corrosive environments (pH 1–14) of electrolytic cells, interface defects (such as pores, stress concentration, and insufficient bonding strength) may lead to increased wear, coating peeling, or decreased catalytic efficiency.

Cemented carbide interface engineering uses physical, chemical or mechanical methods to precisely control the microstructure, chemical bonding and mechanical properties of the interface to optimize the functionality and durability of the material. This technology aims to build a strong and stable interface, enhance the synergy between the substrate and the coating, and between different phases, thereby improving the performance of cemented carbide in complex environments. For example, in aviation nozzles, interface engineering can improve coating adhesion and extend nozzle life by 30-50%; in electrolyzer electrodes, optimizing the catalytic activity of the interface can increase hydrogen evolution efficiency by 10-20%. Interface engineering is not only the key to breakthroughs in cemented carbide performance, but also an important driving force for technological progress in the aviation, energy and manufacturing industries.

2. The main goal of interface engineering

The core of interface engineering is to solve the interface-related problems of cemented carbide in practical applications. Its main goals include:
Enhance interface bonding strength: Improve the adhesion of the coating/substrate or WC/Co interface (e.g. >50 N), prevent peeling or cracking, and meet the high-pressure erosion requirements of aviation nozzles.

Optimizing stress distribution
$^{-6}$ /°C vs Al_2O_3 8×10^{-6} /°C) can be alleviated through interface gradient design or compressive stress induction .

Improve corrosion resistance
Construct a dense interface to block corrosive media (such as sulfuric acid and potassium hydroxide

in the electrolytic cell) and reduce the corrosion rate by 50-90%.

Improve catalytic activity
In electrolyzer electrodes, active sites are increased by interfacial nanostructures, reducing the overpotential for hydrogen/ oxygen evolution (50–200 mV).

Extend service life
Comprehensive optimization of interface performance can extend the life of parts by 20-50%, such as increasing the aviation nozzle from 5,000 hours to 8,000 hours.

3. Main technical methods of cemented carbide interface engineering

Cemented carbide interface engineering technology covers three categories: interface structure design, coating interface optimization and substrate interface modification. The following is an in-depth discussion of the main methods from the perspectives of principle , process and application.

3.1 Interface structure design

By regulating the microstructure of the WC/Co interface, the synergistic effect of the internal phases of the cemented carbide is optimized.

Grain size control
Ultrafine WC powder (particle size 0.2-1 μm) is used and the sintering process (1350-1450°C) is optimized to make the WC/Co interface grain boundary more uniform and increase the interface bonding strength by 20%. This method enhances the toughness of the matrix and is suitable for the impact resistance requirements of aviation nozzles.

Interface doping
Introducing trace additives (such as Cr_3C_2 , VC) at the WC/Co interface inhibits WC grain growth, forms a nanoscale interface layer (thickness 10-100 nm), and increases hardness by 5-10% (HV1600-1800). This technology improves the corrosion resistance of the matrix in the electrolytic cell electrode.

3.2 Coating interface optimization

By designing the transition layer or interface structure between the coating and the cemented carbide substrate, the adhesion and stability are enhanced.

Gradient coating
Using PVD or CVD to deposit multilayer coatings (such as TiN / TiCN / Al_2O_3), the thermal expansion coefficient and hardness are gradually transitioned layer by layer, and the adhesion is improved by 30% (>60 N). In aviation nozzles, gradient coatings reduce thermal stress cracking and extend service life by 40%.

Interface preprocessing

Roughening the substrate surface (Ra 0.8–2 μm) by sandblasting or chemical etching increases the mechanical interlocking effect and improves the coating adhesion by 20%. This method ensures long-term stability in electrolytic cell electrode coatings (such as RuO_2).

Transition layer design

μm thick) between the substrate and the coating improves chemical bonding and reduces interfacial stress. For example, a Ti transition layer increases the adhesion to 70 N in a PVD- TiN coating.

3.3 Matrix interface modification

Directly modify the WC/Co interface or substrate surface through physical or chemical methods to improve interface performance.

Ion implantation

High-energy ions (such as N^+ and C^+) are implanted into the substrate surface (depth 0.1–1 μm) to form a hardened interface layer (hardness HV1500–2000), which improves wear resistance and corrosion resistance. In electrolytic cell electrodes, N^+ implantation increases chlorine evolution efficiency by 15%.

Laser interface modification

The laser beam is used to melt or impact the substrate surface to form a nanoscale interface structure (grain size <100 nm), which increases the hardness by 10% (HV1200-1600). This technology reduces the friction coefficient (0.1-0.2) in the flow channel of aviation nozzles.

Plasma treatment

Plasma (such as Ar , N_2) bombards the substrate surface to remove oxides and induce compressive stress, increasing the interface bonding strength by 20%. In the electrolytic cell, plasma treatment enhances the acid resistance of the coating.

4. Application scenarios of interface engineering

Cemented carbide interface engineering has shown wide application value in aviation nozzles, electrolytic cells and other high-performance fields:

Aviation Nozzle

Gradient coatings (such as TiN / Al_2O_3) optimize the coating/substrate interface, improve adhesion by 30% , and extend the life of fuel nozzles under high-speed airflow erosion by 40% (from 5,000 hours to 7,000 hours). Grain size control enhances the toughness of the WC/Co interface and meets the thermal fatigue resistance requirements of cooling nozzles.

Electrolyzer electrodes

Ion implantation and transition layer design improve the catalytic activity of the electrode interface, reduce the hydrogen evolution overpotential (100-150 mV), and increase efficiency by 10-15%. For example, the PEM electrolyzer uses N^+ - implanted WC-Co electrodes, which reduces the amount of precious metals by 60% and increases the lifespan to 15,000 hours.

Cutting Tools

Interface doping (such as Cr_3C_2) optimizes the WC/Co interface, increases the hardness by 5%, and the wear resistance by 30%, making it suitable for high-speed cutting.

Mining picks

Laser interface modification forms a hardened layer, which improves wear resistance by 20% and extends service life.
Case: The GE9X engine fuel nozzle uses PVD- TiN gradient coating, with an interface adhesion of 70 N, a 30% increase in wear resistance, and improved combustion efficiency.

5. Advantages and Challenges

5.1 Advantages

Performance breakthrough

Interface engineering significantly improves coating adhesion (>50 N), corrosion resistance and catalytic activity, extending component life by 20–50% and increasing efficiency by 10–20%.

Collaborative Optimization

By regulating the WC/Co or coating/substrate interface, the synergistic effect between the substrate and the functional layer is enhanced to meet the composite working conditions of aviation nozzles and electrolytic cells.

Strong flexibility

From nanoscale doping to gradient coatings, the technology can be tailored for different applications, such as catalytic interfaces in electrolyzers or wear-resistant interfaces in nozzles.

Cross-field application

The technology is applicable to multiple fields such as aviation, energy, and manufacturing, demonstrating broad engineering value.

5.2 Challenges

Process complexity

Interface engineering requires precise control of the microstructure (such as grain size and transition layer thickness) and has high requirements for equipment and processes (such as PVD equipment costing RMB 10-30 million).

High cost

Technologies such as ion implantation and laser modification have high operating energy consumption (500–1000 kWh/batch), which limits their large-scale application.

Interface stability

Under long-term high temperature or corrosive environment, the interface may degrade (such as coating peeling and catalytic site deactivation), and the interface design needs to be optimized.

Material compatibility

The difference in thermal expansion coefficients of different phases may lead to interface cracking, and new transition materials need to be developed.

Environmental impact

CVD and ion implantation involve chemical gases or high energy consumption, and green process improvements are needed.

6. Future development trends

In order to overcome the challenges and promote the development of cemented carbide interface engineering, the following directions can be focused on in the future:

Multi-scale interface design

Combining nanoscale doping (<100 nm) and micron-scale transition layers (1–10 μm) improves interface bonding and stability, and durability is increased by 30–50%.

Green Interface Technology

Develop low-temperature PVD/CVD (<500°C) or plasma-enhanced processing to reduce energy consumption by 30–50% and reduce chemical emissions.

Smart interface optimization

Using AI and molecular dynamics simulation, we can predict interface stress distribution and catalytic performance, shortening the R&D cycle by 30%.

Composite Function Interface

Developing catalytic-corrosion-resistant composite interfaces (such as MoN / TiN) can increase the efficiency of electrolyzer electrodes by 20% and reduce the use of precious metals by 70%.

Additive Manufacturing Integration

Combining 3D printed carbide substrate with in-situ interface modification, integrated manufacturing of complex parts can be achieved, reducing costs by 20–30%.

7. Technical characteristics of cemented carbide interface engineering

technology	Mechanism of action	Typical Applications	Key Benefits	Main limitations	Application Effect
Grain size control	Optimizing WC/Co interface grain boundaries	Nozzle, cutter	Toughness +20%, Hardness +5%	Sintering process is complicated	Nozzle impact resistance +30%
Interface doping	Introducing Cr_3C_2 and VC	Electrode, pick	Hardness +5–10%, corrosion resistance	Difficulty in controlling additives	Electrode corrosion resistance +20%
Gradient coating	PVD/CVD multi-layer transition	Nozzle, electrode	Adhesion +30%, thermal stress resistance	High equipment cost	Nozzle life +40%
Interface preprocessing	Sandblasting, chemical etching	Electrode, tool	Bonding strength +20%, simple process	Increased surface roughness	Electrode stability +25%
Ion implantation	N^+ , C^+ embedding interface	Electrode, nozzle	Catalytic activity +15%, no interface	Limited depth and high cost	Hydrogen evolution efficiency +10%
Laser modification	Nanoscale interface hardening	Nozzle, pick	Friction coefficient 0.1-0.2, high precision	High energy consumption	Channel wear resistance +20%
Plasma treatment	Remove oxides, compressive stress	Electrode, tank	Bonding strength +20%, acid resistance	Complex equipment	Electrode corrosion resistance +30%

illustrate:
Mechanism of Action: Overview of the core mechanism of the technology.
Typical applications: aviation nozzles, electrolyzers, etc.
Pros and Cons: Compare performance and limitations.
Application effect: Highlight the contribution in nozzle and electrolytic cell.
Data source: USGS 2024 report and cemented carbide technical standards.

Cemented carbide interface engineering provides breakthrough solutions for high-performance applications such as aviation nozzles and electrolytic cell electrodes by precisely controlling the microstructure and properties of the WC/Co interface and the coating/substrate interface. Gradient coating, ion implantation and other technologies significantly enhance interface bonding, corrosion resistance and catalytic activity, extending nozzle life by 40% and improving electrolysis efficiency by 10-20%. Although process complexity, cost and interface stability remain challenges, the integration of multi-scale design, green processes and intelligent optimization will push the technology to new heights. Interface engineering is not only the key to improving the performance of cemented carbide, but also injects strong impetus into the sustainable development of the aviation, energy and manufacturing fields, demonstrating the deep synergy of materials science and engineering applications.

appendix:

Cemented Carbide Surface Modification Technology

1. The connotation and significance of cemented carbide surface modification

Cemented carbide (WC-Co) has tungsten carbide (WC) as a hard matrix and cobalt (Co) as a binder phase. With its excellent hardness (HV1000–1800), wear resistance and high temperature stability, it has become a core material in high-performance fields such as cutting tools, mining picks and aviation nozzles. However, under extreme working conditions, such as high-temperature gas erosion (1000–1600°C), high-pressure impact (10–30 MPa) or fuel sulfide corrosion faced by aviation nozzles, the surface of cemented carbide may suffer from wear, oxidation or fatigue failure, limiting its service life and reliability. Cemented carbide surface modification technology uses physical, chemical or mechanical means to precisely control the chemical composition, microstructure or physical properties of the surface layer, thereby significantly improving the surface performance while retaining the excellent mechanical properties of the matrix material. This technology is not only the key to extending the life of parts, but also an important driving force for technological progress in industries such as aviation and manufacturing.

The core goal of surface modification is to optimize the performance of cemented carbide in specific environments. For example, in aviation nozzles, surface modification can enhance wear resistance to cope with high-speed airflow scouring, improve corrosion resistance to resist fuel chemical erosion, or improve high temperature resistance to adapt to extreme conditions in the combustion chamber. These improvements not only extend the life of the nozzle (from 5,000 hours to 8,000 hours), but also improve combustion efficiency (5–10%), supporting energy conservation, emission reduction and performance optimization of aviation engines. In addition, surface modification technology can further meet the needs of diverse applications such as cutting tools and molds by reducing the friction coefficient or enhancing fatigue resistance, demonstrating its wide range of engineering value‽ web :9,23 ‽ .

2. Main approaches to cemented carbide surface modification technology

Cemented carbide surface modification technologies cover three categories: surface coating technology, surface chemical modification, and surface mechanical modification. Each type of technology injects specific functions into the surface of cemented carbide through different mechanisms of action to meet the challenges of complex working conditions. The following is an in-depth discussion of the characteristics of each type of technology from the perspective of process principles, application scenarios, and effects.

2.1 Surface coating technology: building a protective barrier

Surface coating technology deposits one or more layers of functional materials (such as ceramics, metals or composites) on the surface of cemented carbide to provide a protective barrier for the substrate, significantly improving wear resistance, corrosion resistance and high temperature resistance. This technology is particularly common in aviation nozzles because it can effectively deal with high temperature erosion and chemical corrosion.

Physical vapor deposition (PVD)
PVD uses physical processes (such as sputtering or evaporation) in a vacuum environment to deposit coating materials (such as titanium nitride TiN and aluminum oxide Al_2O_3) in atomic or molecular form onto the surface of cemented carbide to form a film with a thickness of 1–10 μm . The PVD process temperature is low (200–500°C), which avoids degradation of substrate performance. The coating hardness can reach HV2000–3000 and has strong adhesion (>50 N). In aviation nozzles, TiN coatings can significantly improve the wear resistance of fuel nozzles, extending their service life by 30% under high-speed airflow scouring. However, PVD coatings are thin and may peel off in the face of extreme impact, limiting their application under heavy-load conditions.

Chemical vapor deposition (CVD)
CVD converts gaseous precursors (such as titanium tetrachloride $TiCl_4$) into solid coatings (such as titanium carbide TiC , Al_2O_3) with a thickness of 5–20 μm through high-temperature (800–1000°C) chemical reactions. CVD coatings are thick and dense, and are particularly suitable for high-temperature environments, such as the Al_2O_3 coating of turbofan engine cooling nozzles , which can withstand high temperatures of 1500°C and resist oxidative corrosion. However, high-temperature processes may cause the substrate cobalt phase to soften , increase the difficulty of process control, and have high equipment costs (approximately RMB 10–30 million).

Thermal spraying Thermal spraying forms a coating with a thickness of 50–500
μm on the surface by spraying molten or semi-molten materials (such as WC-Co, chromium carbide Cr_3C_2) at high speed . This technology is suitable for large parts, such as the throat of gas turbine nozzles, and its thick coating can effectively resist high-speed gas erosion. However, the thermal spray coating has low bonding strength (20–40 MPa) and a rough surface (Ra 2–5 μm), which requires subsequent processing to meet the precision requirements of aviation nozzles (such as Ra <0.4 μm).

2.2 Surface chemical modification: reshaping the surface structure

Surface chemical modification enhances the surface properties of cemented carbide by introducing new elements or changing the chemical composition of the surface layer. This method directly acts on the surface of the material to form a modified layer that seamlessly connects with the substrate, which is particularly suitable for high-precision parts.

implantation
uses high-energy ion beams (such as nitrogen N^+ , carbon C^+) to bombard the surface, embedding ions into the surface layer (depth 0.1-1 μm), forming hardened compounds (such as WN, WC), and improving hardness (HV1500-2000) and wear resistance. Ion implantation has no obvious coating

interface and maintains the properties of the substrate. It is suitable for wear-resistant strengthening of the micropore surface of aviation nozzles, and the wear resistance can be improved by 20%. However, the limited modification depth and high equipment cost (about 10 million RMB) limit its application on large-area parts.

Chemical heat treatment (carburizing, nitriding)

Chemical heat treatment uses high temperature (800-1000°C) to penetrate carbon or nitrogen atoms into the surface to form a hard compound layer (thickness 10-100 μm). The surface hardness of nitrided cemented carbide can reach HV1500-2000, and the wear resistance is significantly improved, which is suitable for wear-resistant parts of mining picks or aviation nozzles. However, high temperature may reduce the toughness of the matrix, and the process parameters need to be precisely controlled to balance the performance.

2.3 Surface mechanical modification: Optimizing morphology and stress

Surface mechanical modification changes the surface morphology or stress state through physical action to enhance fatigue resistance or wear resistance. This method is simple in process, low in cost and suitable for a variety of working conditions.

Shot peening

Shot peening uses high-speed projectiles (such as steel shots and ceramic shots) to bombard the surface, inducing compressive stress and improving fatigue resistance. Shot peening can extend the fatigue life of aviation nozzle flow channels by 30%, and is particularly suitable for parts subjected to cyclic thermal stress. However, shot peening increases surface roughness (Ra 0.8–2 μm), which may affect fluid efficiency and require subsequent polishing.

Laser surface modification

Laser surface modification uses a laser beam to melt or impact the surface to form a hardened layer (depth 0.1-1 mm) or micro-nano structure , increase hardness (HV1200-1600) and reduce friction coefficient (0.1-0.2). On the surface of micropores in aviation nozzles, laser modification can optimize fluid dynamics and reduce adhesive wear. However, laser equipment is expensive (about 5 million yuan) and consumes a lot of energy , so the process needs to be optimized to reduce operating costs.

3. Application of cemented carbide surface modification in aviation nozzles

As the core components of aircraft engines (turbofans, turboshafts) and gas turbines, aviation nozzles need to operate stably in high temperature, high pressure and corrosive environments. Cemented carbide surface modification technology significantly enhances the performance and life of nozzles by improving wear resistance, corrosion resistance and high temperature resistance. For example:

Fuel Nozzle

PVD- TiN coating is applied to GE9X engine fuel nozzles (diameter 0.1-0.5 mm), which improves wear resistance by 30%, increases service life from 5,000 hours to 7,000 hours, and increases combustion efficiency by 5%.

Cooling nozzle

CVD-Al_2O_3 coating is used for turbofan engine cooling hole nozzles. It can withstand high temperatures of 1500°C, reduce oxidation corrosion, and extend maintenance cycles by 30 % .

Nozzle throat

Thermal sprayed WC-Co coatings are used in gas turbine nozzles to resist high-speed gas erosion and extend service life by 20%.

Flow channel surface: Shot peening and laser modification enhance the flow channel's fatigue resistance, adapt to cyclic thermal stress, and increase fatigue life by 30%.

These applications not only improve the reliability of nozzles, but also optimize the fuel efficiency and emission performance of engines, contributing to the sustainable development of the aviation industry ‽ web:9 ‽ .

4. Advantages and limitations of cemented carbide surface modification technology

Cemented carbide surface modification technology provides significant performance improvements for high-performance parts, but it also has certain limitations:

Advantages of cemented carbide surface modification technology:

Performance Optimization

Wear resistance, corrosion resistance and high temperature resistance are improved by 20-50%, extending the life of parts and meeting harsh working conditions such as aviation nozzles.

Substrate protection

The modification only acts on the surface, retaining the excellent strength (2000–2500 MPa) and toughness of the WC-Co matrix.

Flexible customization

From thin-film coatings (PVD) to thick coatings (thermal spraying), from hardened layers (ion implantation) to micro-nanostructuring (laser), the technology can be selected according to the requirements.

Limitations of cemented carbide surface modification technology:

High cost

The equipment investment is large (e.g. PVD/CVD furnace is RMB 10–30 million) and the operating energy consumption is high (500–1000 kWh per batch).

Complex process

Parameters (such as CVD temperature and ion implantation dose) need to be precisely controlled, and the surface state of the substrate affects the effect.

Applicability Limitations

Thin coatings (PVD 1–10 μm) are susceptible to peeling under heavy erosion, and the depth of chemical modification (0.1–100 μm) is not sufficient to cope with long-term wear.

5. Challenges of cemented carbide surface modification technology

Although cemented carbide surface modification technology has shown great potential in fields such as aviation nozzles, its promotion and application still faces the following challenges:

Economical

The cost of high-performance equipment and processes limits their application in small and medium-sized enterprises, especially in mass production, where performance and cost need to be balanced .

Stability and reliability

The coating adhesion (20–50 MPa) or the uniformity of the modified layer is affected by the cleanliness and roughness of the substrate surface, and the pretreatment technology needs to be improved.

Adaptability to extreme working conditions

The long-term performance of aviation nozzles under high-temperature erosion and cyclic stress still needs to be verified, and the peeling of thin coatings or wear of modified layers are key bottlenecks.

Environmental Sustainability

CVD involves chemical gas emissions, thermal spraying and laser modification have high energy consumption, and green processes need to be developed to meet environmental protection requirements.

Material compatibility

The difference in thermal expansion coefficient between the modified layer and the WC-Co matrix (e.g., Al_2O_3 8×10^{-6} /°C vs WC-Co 5–7×10^{-6} /°C) may cause thermal stress cracking, and the interface design needs to be optimized.

6. Future development direction of cemented carbide surface modification technology

In order to meet the challenges and further enhance the application value of cemented carbide surface modification technology, breakthroughs can be made in the following directions in the future:

Multi-layer composite coating

PVD /CVD multilayer structures (such as TiN / Al_2O_3 / TiC), combining high hardness and high toughness, improving wear resistance by 50% and anti -peeling ability by 30%, meeting the complex working conditions of aviation nozzles .

Green process innovation

Promote low-temperature CVD (<600°C) or plasma-enhanced PVD to reduce energy consumption by 30–50%; develop environmentally friendly precursors to reduce chemical emissions.

Smart surface design

Through laser micro-nanostructure or self-lubricating coating (such as MoS_2 , DLC), the friction coefficient can be reduced to below 0.1, thereby improving the nozzle fluid efficiency.

Additive Manufacturing Integration

Combining 3D printed carbide substrates with surface modification (such as in-situ laser modification) can achieve integrated manufacturing of complex parts and reduce costs by 20-30%.

Data-driven optimization

Utilize artificial intelligence and molecular dynamics simulation to predict coating performance and lifespan, shorten the R&D cycle by 30%, and accelerate technology iteration.

7. Summary

Technical characteristics of cemented carbide surface modification

technology	Mechanism of action	Typical Applications	Key Benefits	Main limitations	Aviation nozzle effect
PVD	Physical Deposition Thin Films 1–10	Cutting tools, nozzle micropores	High hardness HV2000–3000, low temperature process	Thin coating, weak impact resistance	Fuel nozzle wear resistance +30%, life span 7000 hours
CVD	Chemical deposition thick coating 5–20	Nozzle, pick	High temperature resistance 1500°C, corrosion resistance	High temperature damages the substrate and is costly	Cooling nozzle temperature resistance 1500°C, maintenance cycle +30%
Thermal Spraying	Spraying thick coating 50–500	Nozzle throat, mold	Anti-erosion, thick coating	Low binding force and poor precision	Gas turbine nozzle life +20%
Ion implantation	Ion embedding hardening layer 0.1–1	Knife, Nozzle	No interface, high precision	Limited depth and expensive equipment	Micropore wear resistance +20%
Chemical heat treatment	Carburizing/nitriding hardening 10–100	Pick, Nozzle	High hardness, moderate cost	High temperature affects toughness	Hardness of wear-resistant parts: HV1500–2000
Shot Peening	Projectile-induced compressive stress	Nozzle flow channel	Anti-fatigue, low cost	Increased roughness	Runner fatigue life +30%
Laser modification	Laser hardening/ micro-nanostructure	Nozzle, mold	High precision and low friction	High energy consumption and high cost	Micropore friction coefficient 0.1–0.2

illustrate:
Mechanism of Action: Overview of the core principles of the technology.
Typical applications: List the main usage scenarios.

Pros and Cons: Compare performance and limitations.
Aero nozzle effect: Highlights the specific contribution in the nozzle.
Data source: USGS 2024 report and cemented carbide technical standards ‽ web:9,23 ‽ .

in conclusion

Through sophisticated coating, chemical or mechanical treatment, cemented carbide surface modification technology gives WC-Co materials excellent wear resistance, corrosion resistance and high temperature resistance, making it shine in high-performance fields such as aviation nozzles and cutting tools. In aviation nozzles, PVD and CVD coatings effectively deal with high-temperature erosion, shot peening and laser modification significantly improve fatigue resistance, comprehensively extend part life by 20-50%, and optimize combustion efficiency by 5-10%. Although high cost, process complexity and adaptability to extreme working conditions remain challenges, the integration of multi-layer composite coatings, green processes and additive manufacturing will push technology to a higher level. Cemented carbide surface modification technology is not only the forefront of innovation in materials science, but also injects strong impetus into the efficient, reliable and sustainable development of the aviation industry, demonstrating the deep integration of science and engineering.

CTIA GROUP LTD

30 Years of Cemented Carbide Customization Experts

Core Advantages

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

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

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

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appendix:

Application of Cemented Carbide Nanocomposite Coating in Electrolytic Cell

1. Background of cemented carbide and nanocomposite coating

Cemented carbide (WC-Co), with tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase, is widely used in aviation nozzles, cutting tools and industrial wear-resistant parts due to its high hardness (HV1000–1800), excellent wear resistance and high temperature stability. However, in extreme environments such as electrolytic cells, such as strong acid and alkali electrolytes (pH 1–14), high temperatures (50–80°C) and high current densities (0.1–10 A/cm^2) , cemented carbide surfaces may face challenges such as corrosion , wear or insufficient catalytic performance. Nanocomposite coatings, as an advanced surface modification technology, significantly improve the corrosion resistance, catalytic activity and mechanical properties of cemented carbide surfaces by combining nanoscale particles (such as SiC , TiO_2 , CNT) or thin films (thickness 1–100 nm) with metal or ceramic matrices, providing an ideal solution for electrodes, tanks or corrosion-resistant parts in electrolytic cells.

The application of nanocomposite coatings in electrolyzers is mainly focused on improving the electrocatalytic efficiency of electrodes, extending corrosion resistance life, and reducing the use of precious metals (such as platinum and iridium). For example, in hydrogen electrolyzers (such as PEM electrolyzers), nanocomposite coatings can reduce the platinum loading by 10-40 times while maintaining high catalytic activity. In the field of aviation nozzles, similar technologies are also used to enhance wear resistance and corrosion resistance, indicating its wide applicability under extreme working conditions.

Through precise coating design, cemented carbide nanocomposite coatings not only optimize the performance of electrolytic cells, but also promote the sustainable development of green energy technology.

2. Characteristics of cemented carbide nanocomposite coating

Nanocomposite coatings are composed of at least two immiscible phases (such as metal matrix and nanoparticles), and the interface region has a nanoscale structure (grain or particle size <100 nm). Its unique properties are derived from the synergistic effect of nano effects, including small size effect, interface enhancement and quantum effect. The following are its main characteristics:

High hardness and wear resistance
Nanoparticles (such as SiC , Al_2O_3) are embedded in the matrix (such as Ni-P, WC-Co), with a hardness of up to HV2000–3000 and wear resistance increased by 30–50%, which is suitable for the mechanical wear that electrolytic cell electrodes are subjected to.

Excellent corrosion resistance

The dense structure and chemical inertness of the nano-coating (such as TiN and MoN) effectively block corrosive electrolytes (such as sulfuric acid and potassium hydroxide), reducing the corrosion rate by 50–90%.

Highly efficient electrocatalysis

Nanoscale active sites (such as RuO_2 and IrO_2) increase the surface reaction area, reduce the hydrogen/ oxygen evolution overpotential (50–200 mV), and improve the electrolysis efficiency by 10–20% .

Thermal stability

The coatings remain stable at the electrolyzer operating temperature of 50–80°C, and some coatings (such as Al_2O_3 - TiO_2) can withstand higher temperatures (>200°C).

Low precious metal dependence

with nanoparticles (such as MoN and CNT) can reduce costs by 50–80%, meeting the needs of green manufacturing.

These properties make nanocomposite coatings ideal for electrolyzer electrodes and corrosion-resistant components, particularly in hydrogen energy production (e.g., water electrolysis) and the chlor-alkali industry .

3. Preparation method

The preparation of cemented carbide nanocomposite coatings requires consideration of coating uniformity, adhesion and precise control of nanostructure. The following are the main methods, analyzed in combination with the application characteristics of electrolytic cells:

3.1 Physical Vapor Deposition (PVD)

TiN and ZrO_2) on the surface of cemented carbide by sputtering or evaporation to form a film with a thickness of 1–10 μm . The process temperature is low (200–500°C), which is suitable for the preparation of precision coatings for electrolytic cell electrodes. PVD coatings have high hardness (HV2000–3000) and strong adhesion (>50 N). They are used to deposit TiN coatings in PEM electrolytic cells to improve the corrosion resistance and catalytic activity of electrodes. However, PVD coatings are thin and have limited resistance to heavy-load wear.

3.2 Chemical Vapor Deposition (CVD)

CVD deposits thick coatings (5–20 μm), such as TiC or Al_2O_3 - TiO_2 , through high-temperature (600–1000°C) chemical reactions , which are suitable for corrosion protection of electrolytic cell bodies or electrodes. CVD coatings are dense and resistant to high temperatures, but they may cause softening of the cobalt phase of cemented carbide at high temperatures , and the process needs to be optimized to reduce the deposition temperature. Chlor-alkali electrolytic cells often use CVD- RuO_2 coated electrodes, which increase chlorine evolution efficiency by 15%.

3.3 Electroless Plating

Electroless deposition deposits a Ni-P based nanocomposite coating on the surface of cemented carbide by chemical reduction, embedding nanoparticles (such as SiC , CNT). The coating thickness is controllable (5–50 µm), with high uniformity, suitable for complex geometry electrodes. After heat treatment, the Ni_3P phase crystallizes to increase the hardness to HV1500–2000 and the wear resistance is improved by 30%. In the electrolytic cell, Ni-P/ SiC coating is used for corrosion-resistant electrodes, and the cost is lower than PVD/CVD.

3.4 Electrodeposition

Electrodeposition deposits Co-P or Ni-P based nanocomposite coatings through electrochemical reactions, doped with nanoparticles (such as Al_2O_3 , TiO_2) . The process is simple, low cost (equipment is about RMB 1-5 million), and suitable for large-scale production. Co-P/ Al_2O_3 coatings exhibit high corrosion resistance on electrolytic cell electrodes , reducing the corrosion rate by 70%. However, the uniformity of the electrodeposited coating is affected by the current density, and the process parameters need to be optimized .

3.5 Plasma Electrolytic Oxidation (PEO)

Al_2O_3) in the electrolyte through high voltage (350–500 V) , with a thickness of 3–10 µm , which is suitable for corrosion protection of cemented carbide tanks or electrodes. PEO coating has low porosity and excellent corrosion resistance, and is suitable for alkaline electrolytic cells (such as KOH electrolyte). Adding nanoparticles (such as V_2O_5) can further improve the electrocatalytic performance, with a COD removal rate of 90 %.

4. Application scenarios in electrolyzers

Cemented carbide nanocomposite coatings are mainly used for electrodes, tank bodies and corrosion-resistant parts in electrolytic cells. Typical applications include:

Hydrogen electrolyzer (PEM, alkaline electrolyzer)

Nanocomposite coatings (such as MoN and Ni-P/CNT) are used for electrodes to reduce the hydrogen evolution overpotential (100–150 mV), reduce the platinum load by 10–40 times, and improve electrolysis efficiency by 15%. For example, Naco Technologies' MoN coating ranks first in PEM electrolyzers and improves durability by 30%.

Chlor-alkali industry

RuO_2 or IrO_2 nano -coated electrodes are used for chlorine evolution reaction , with the catalytic efficiency increased by 20%, the strong alkali corrosion resistance (pH 14) and the service life extended by 50% .

Electrolysis water treatment

Ni-P/ SiC coated electrodes are used in sewage treatment electrolyzers, with a COD removal rate of 95% and better acid resistance (pH 1–3) than traditional electrodes.

Aviation related electrolysis

In aviation manufacturing, electrolytic cells are used for surface treatment (such as anodizing), and nano-composite coatings (such as TiN) protect electrodes, increasing wear resistance by 30%, which is consistent with the corrosion resistance requirements of aviation nozzles.

Case: A PEM electrolyzer uses Ni-P/ TiO_2 nanocomposite coating electrodes, which increases hydrogen evolution efficiency by 10%, increases service life from 10,000 hours to 15,000 hours, reduces precious metal usage by 60%, and significantly reduces hydrogen production costs.

5. Advantages and Challenges

5.1 Advantages

Excellent performance

The hardness (HV2000–3000), corrosion resistance and catalytic activity of the nano coating are significantly better than those of traditional coatings, and the electrolysis efficiency is increased by 10–20%.

Cost savings

Reduce the use of precious metals (such as Pt, Ir), reduce production costs by 50–80%, and are suitable for large-scale green energy applications.

High uniformity

Electroless deposition and PEO technologies enable uniform coating of complex electrodes, suitable for microchannels or porous structures.

Environmentally friendly

Nano coatings extend electrode life, reduce replacement frequency, and reduce resource consumption and waste discharge.

5.2 Challenges

Preparation cost

PVD/CVD equipment is expensive (RMB 10–30 million) and consumes high operating energy (500–1000 kWh/batch), limiting small and medium-sized applications.

Coating stability

Nanocoatings may peel off under long-term high current density, and the adhesion (20–50 MPa) needs to be further improved.

Process complexity

Nanoparticle dispersion and coating uniformity are affected by the surface state of the substrate and require strict pretreatment.

Environmental impact

CVD involves chemical gas emissions, and the cost of treating electroless deposition waste liquid is high, so green processes need to be developed.

Nanotoxicity

Some nanoparticles (such as CNTs) may be environmentally toxic, so non-toxic materials (such as SiC and Al_2O_3) need to be selected .

6. Future Development Direction

In order to overcome the challenges and promote the application of cemented carbide nanocomposite coatings in electrolytic cells, the following directions can be focused on in the future:

Multifunctional composite coating

Develop multi-layer nano-coatings (such as TiN / RuO_2 / MoN) that combine high catalytic activity with corrosion resistance to increase electrolysis efficiency by 20–30%.

Green preparation technology

Promote low-temperature CVD (<500°C) or plasma-enhanced electroless deposition to reduce energy consumption by 30–50% and reduce chemical waste.

Nanoparticle Optimization

Using non-toxic nanoparticles (such as SiO_2 and TiO_2) to replace precious metals can reduce costs by 50% while improving environmental safety.

Additive Manufacturing Integration

Combining 3D printed carbide electrodes with in-situ deposition of nano-coatings, integrated manufacturing of complex structures is achieved, reducing costs by 20%.

Intelligent monitoring and design

Through AI and molecular dynamics simulation, the coating structure is optimized, the life and performance are predicted, and the R&D cycle is shortened by 30%.

7. Summary table

Key characteristics and technical points of cemented carbide nanocomposite coating in electrolytic cell

technology	Mechanism of action	Typical Applications	Key Benefits	Main limitations	Electrolyzer Effect
PVD	Physical deposition of nanofilms (1–10 μm)	PEM electrolyzer electrodes	High hardness (HV2000–3000), high catalytic activity	Thin coating, high cost	Hydrogen evolution efficiency +10%, life span +30%
CVD	Chemically deposited thick	Chlor-alkali	High temperature	High temperature	Chlorine evolution

	coatings (5–20 μm)	electrode	resistance (1500°C), corrosion resistance	damage to the substrate	efficiency +15%, life span +50%
Electroless Deposition	Chemically reduced Ni-P based coatings (5–50 μm)	Sewage treatment electrode	High uniformity and low cost	Wastewater treatment is complicated	COD removal rate 95%, strong acid resistance
Electrodeposition	Electrochemically deposited Co-P based coatings (5–50 μm)	Hydrogen Electrode	Simple process, corrosion resistance	Uniformity needs to be optimized	Corrosion rate -70%, low cost
PEO	Plasma oxidation ceramic coating (3–10 μm)	Alkaline electrolyzer	Low porosity, corrosion resistance	High voltage, high energy consumption	COD removal rate 95%, strong alkali resistance

illustrate:
Mechanism of Action: Overview of the core mechanism of the technology.
Typical applications: List electrolyzer-related scenarios.
Pros and Cons: Compare performance and limitations.
Electrolyser effect: highlights the specific contribution in the electrolyser.
Data source: USGS 2024 report and related technical documents. web:0,1,9,14,23

8. Conclusion

Cemented carbide nanocomposite coatings provide excellent wear resistance, corrosion resistance and electrocatalytic performance for electrolyzer electrodes and corrosion-resistant parts by combining nanoscale particles or films with WC-Co matrix. In hydrogen electrolyzers, chlor-alkali industry and sewage treatment, the coatings significantly improve electrolysis efficiency (10–20%), extend life (30–50%) and reduce dependence on precious metals, showing its great potential in the field of green energy. Similar to the corrosion resistance requirements of aviation nozzles, the application of nanocomposite coatings in electrolyzers reflects cross-domain innovation in materials science. However, high preparation costs, coating stability and environmental impact still need to be overcome. In the future, through the integration of multifunctional composite coatings, green processes and additive manufacturing , cemented carbide nanocomposite coatings will further promote the development of electrolyzer technology in an efficient and sustainable direction, injecting new impetus into global energy transformation and industrial upgrading.

appendix:

What is Nano-coated Cemented Carbide

Nano-coated cemented carbide refers to a coating with a thickness of nanometers (usually 1100 nm) deposited on the surface of a cemented carbide substrate (such as WC+Co , WC+Ni) by physical or chemical methods to significantly improve wear resistance, corrosion resistance, high temperature resistance and surface properties, while maintaining the high hardness (14002200 HV) and strength (1.82.8 GPa) of the substrate. Nano-coatings are widely used in aviation tools, deep-sea seals, chemical pump bodies and molds due to their ultra-fine grain structure (grain size <100 nm), high interface density and excellent adhesion, meeting the requirements of extreme working conditions (such as high temperature 8001200°C, high pressure 15,000 psi, corrosive fluids).

This article combines national standards (such as GB/T 183762014, GB/T 79972017) and industry practices to introduce in detail the definition, coating types, preparation process, performance and applications of nano-coated cemented carbide, and appropriately recommends the production capabilities of CTIA GROUP LTD in the fields of nano-coated cemented carbide seals, pump bodies, etc.

1. Definition and significance of nano-coated cemented carbide

Nano-coated cemented carbide consists of a cemented carbide substrate and a nanoscale coating. The coating thickness is usually 110 μm (single layer or multilayer) and the grain size is <100 nm. It is prepared by physical vapor deposition (PVD), chemical vapor deposition (CVD) or composite technology (such as plasma spraying).

Matrix
WC (85-94%) + bonding phase (Co/Ni, 6-15%), density 14.5-15.0 g/cm^3 , porosity <0.01% (GB/T 5169-2013).

coating
Common materials include TiN , TiAlN , Al2O3, DLC (diamond-like carbon), CrN , etc., which have high hardness (20004000 HV), low friction coefficient (<0.2) and excellent corrosion resistance.

Wear resistance
Nano coating has high hardness (20004000 HV), reduces wear by 3050% (ASTM G65), and extends tool life by 25 times .

Corrosion resistance
The coating is dense (porosity <0.001%) and resistant to acid (H2SO4), alkali (NaOH), and seawater corrosion with a rate of <0.005 mm/y (NACE MR0175).

High temperature resistance

TiAlN and Al2O3 coatings are resistant to oxidation at 8001200°C and are suitable for high-speed cutting and high-temperature conditions.

Surface properties

Friction coefficient reduced by 2050% (DLC <0.1), improved sealing performance (leakage rate $<10^{-6}$ mbar·L /s).

Applications : aviation tools (cutting life increased by 50%), deep-sea seals (resistant to H2S/seawater), chemical pump bodies (erosion and corrosion resistance increased by 30%).

2. Nano coating types and characteristics

Single layer nano coating :

Material :

TiN : golden yellow, hardness 20002300 HV, good wear resistance, temperature resistance 600°C.

CrN : Silver gray, hardness 18002200 HV, excellent corrosion resistance (resistant to Cl^- / H2S), friction coefficient 0.30.4.

DLC : black, hardness 20003000 HV, friction coefficient <0.1, strong wear/corrosion resistance.

Thickness : 15 μm , grain size: 1050 nm.

Applications : molds, seals (CrN /DLC), low-speed cutting tools (TiN).

Multi-layer nano coating :

Material :

TiN / TiAlN : alternating layers (1020 nm/layer), hardness 25003000 HV, temperature resistance 8001000°C.

TiAlN /Al2O3 : Hardness 30003500 HV, oxidation resistance 10001200°C, wear resistance increased by 30%.

CrN / AlCrN : Hardness 22002800 HV, corrosion resistance increased by 2030%, suitable for marine environment.

Thickness : 210 μm , number of layers: 101000.

Features : Multi-layer structure enhances interface stress dispersion and increases crack growth resistance by 50%.

Application : high-speed cutting tools (TiAlN /Al2O3), deep-sea valves (CrN / AlCrN).

Gradient Nano Coating :

Materials : TiCN , AlCrSiN , with a gradual change in composition from matrix to surface (such as Ti→TiN→TiCN).

Features : Hardness 25003500 HV, adhesion increased by 2030% (scratch test>80 N), balanced wear / corrosion resistance.

Application : Chemical pump bodies, aviation cutting tools, erosion and corrosion resistance increased by 30%.

Composite nano coating :

Material : DLC+TiN , Al2O3+CrN, combining the advantages of multiple materials .

Features : hardness 20004000 HV, friction coefficient <0.2, temperature resistance 8001000°C, corrosion resistance increased by 2050%.

Application : Seals (DLC+CrN , leakage rate $<10^{-6}$ mbar·L /s), high speed mold.

3. Nano coating preparation process

Physical Vapor Deposition (PVD) :

method :

Magnetron sputtering : high deposition rate (0.11 µm /h), suitable for TiN , CrN , and DLC.

Arc evaporation : high ionization rate (>80%), suitable for TiAlN and AlCrN .

Process :

Vacuum degree: 10^{-3} 10^{-4} Pa.

Temperature: 200500°C (avoid substrate annealing).

Bias: 50 to 200 V, enhances adhesion.

Gas: Ar (substrate cleaning), N2/CH4 (reaction to form TiN /DLC).

Performance : coating thickness 15 µm , grain size 1050 nm, adhesion >60 N (scratch test).

Advantages : low temperature deposition, suitable for cemented carbide substrate, uniform coating (deviation <±5%).

Limitations : Low deposition rate (0.11 µm /h), slightly poor coverage of complex shapes.

Chemical Vapor Deposition (CVD) :

method :

Thermal CVD : suitable for Al2O3, TiCN , deposition temperature 8001000°C.

Plasma enhanced CVD (PECVD) : suitable for DLC, temperature 200400°C.

Process :

Temperature: 2001000°C (high for thermal CVD, low for PECVD).

Gas: TiCl4 (TiN / TiCN), CH4 (DLC), AlCl3 (Al2O3).

Pressure: 10^{2} 10^{3} Pa .

Properties : thickness 210 µm , grain size 20100 nm, hardness 20003500 HV.

Advantages : Dense coating (porosity < 0.001%), covering complex shapes.

Limitations : High temperature CVD may reduce matrix strength (hardness drops by 5-10%).

Composite Technology :

Plasma spraying : suitable for thick coatings (1050 µm), such as Al2O3+TiN, with grain size of 50100 nm.

Laser cladding : local deposition of TiN / CrN , thickness 520 µm , adhesion >100 N.

Application : Chemical pump bodies and molds, erosion and corrosion resistance increased by 30%.

Post-processing :

Polishing : Ra <0.1 µm , friction coefficient reduced by 1020%.

Annealing : 300-500°C, eliminate internal stress, increase adhesion by 1015%.

Ion cleaning : Ar ion bombardment, surface defects reduced by 20%.

4. Nano-coated cemented carbide performance

Coating Type	Hardness (HV)	Friction coefficient	Temperature resistance (°C)	Corrosion rate (mm/y)	Typical Applications
TiN	20002300	0.40.6	600	0.010.05 (HCl)	Low speed tool
TiAlN	25003000	0.30.5	8001000	0.010.03 (H2SO4)	High speed tool
CrN	18002200	0.30.4	700	<0.005 (sea water)	Seals
DLC	20003000	<0.1	400600	<0.005 (NaOH)	Pump body
Al2O3/ TiAlN	30003500	0.40.5	10001200	0.0050.01 (H2S)	Aviation tools

Performance improvements :

Wear resistance : TiAlN coated tools have a 25- fold increase in cutting life and a wear rate of <0.02 mm^3 / h.

Corrosion resistance : The corrosion rate of CrN /DLC coating in seawater/H2S is <0.005 mm/y, which is better than that of uncoated substrate (0.010.05 mm/y).

High temperature resistance : The oxide layer thickness of Al2O3/ TiAlN coating is less than 0.1 µm during cutting at 1000°C .

Sealing performance : DLC coated seal leakage rate $<10^{-6}$ mbar·L /s, life expectancy increased by 3050%.

Examples :

TiAlN tool : PVD coating (3 µm , 1400°C cutting), life increased by 3 times , wear resistance increased by 50%.

CrN seals : PVD CrN (2 µm), seawater (15,000 psi) corrosion rate <0.005 mm/y, life span >1000 connections.

DLC pump body : PECVD DLC (1 µm), H2SO4 (50%) corrosion rate <0.005 mm/y, erosion resistance increased by 30%.

5. Application scenarios

Aviation knives :

Coating : TiAlN /Al2O3 (35 µm , PVD/CVD).

Performance : hardness 3000-3500 HV, temperature resistance 1000-1200°C, cutting life increased by 50%.

Example : WC+6%Co tool (Ø 12 × 80 mm), TiAlN coating, cutting Ti alloy, life 300 minutes (uncoated 100 minutes).

Deep Sea Seals :

Coating : CrN /DLC (13 µm , PVD).

Performance : H2S/seawater corrosion rate <0.005 mm/y, leakage rate $<10^{-6}$ mbar·L /s.
Example : YN10 seal (Ø 50 mm), CrN coating, 15,000 psi, life > 1000 connections.

Chemical pump body :
Coating : DLC/ TiCN (25 µm , PECVD).
Performance : H_2SO_4 (50%) corrosion rate <0.005 mm/y, wear amount $<0.03\ mm^3$ / h.
Example : YN12 pump housing (Ø 200 mm), DLC coating, fluid containing particles, life span >10,000 hours.
Mould :
Coating : TiN / CrN (13 µm , PVD).
Performance : hardness 20002300 HV, friction coefficient <0.4, mold life increased by 23 times .
Example : WC+8%Co mold (Ø 100 mm), TiN coating, punching life 500,000 times (uncoated 200,000 times).

6. Optimization suggestions for nano-coated cemented carbide

Matrix Optimization :
Material : Ni-based cemented carbide (YN10/YN12) is used, and the corrosion resistance is increased by 5070% (NACE MR0175).
Sintering : HIP (1350°C, 120 MPa), porosity <0.001%, adhesion increased by 20%.
Surface : Polished (Ra <0.2 µm), coating adhesion increased by 1520%.

coating :
Multilayer structure : TiN / TiAlN (1020 nm/layer), crack growth resistance increased by 50%.
Gradient coating : TiCN / AlCrSiN , adhesion increased by 2030%.
Composite coating : DLC+CrN , friction coefficient <0.1, corrosion resistance increased by 30%.

Preparation process :
PVD : Bias 100 V, deposition temperature 300400°C, coating uniformity increased by 10%.
PECVD : low temperature (200-300°C), suitable for DLC, no loss of substrate performance.
Cleaning : Ar ion cleaning (10^{-3} Pa), surface defects reduced by 20%.

Equipment optimization :
Vacuum degree : 10^{-4} Pa, impurities reduced by 30%, coating purity increased by 10%.
Target material : high purity Ti/Al/Cr (>99.99%), coating defects reduced by 20%.
Monitoring : Online spectral analysis, thickness deviation <±5%.

Post-processing :
Polishing : Ra <0.1 µm , friction coefficient reduced by 1020%.
Annealing : 400°C, internal stress decreases by 15%, adhesion increases by 10%.
Coating inspection : scratch test (>60 N), SEM observation of grains (<50 nm).

7. Standards

GB/T 183762014 : Porosity <0.01%, uniformity >95%.
GB/T 51692013 : Porosity A00B00C00 (HIP substrate).
GB/T 38502015 : Density deviation <±0.1 g/ cm^3 .
GB/T 79972017 : Hardness 1400-2200 HV (substrate), 2000-4000 HV (coating).
GB/T 38512015 : Flexural strength 1.82.8 GPa .
NACE MR0175 : H2S/CO2 resistant, corrosion rate <0.005 mm/y.
ISO 6508 : Coating hardness test, deviation < ±50 HV.
ASTM G65 : Wear rate <0.05 mm^3 / h.

8. Conclusion

Nano-coated cemented carbide significantly improves wear resistance (wear loss reduced by 30-50%), corrosion resistance (corrosion rate <0.005 mm/y) and high temperature resistance (800-1200°C) by depositing nano-scale coatings (TiN , TiAlN , CrN , DLC, etc.) on WC+Co/Ni substrates, meeting the stringent requirements of aviation tools, deep-sea seals and chemical pump bodies. The PVD/PECVD process ensures that the coating is dense (grains <50 nm) and has strong adhesion (>60 N), and multi-layer/gradient coatings further optimize performance. Optimizing the substrate (HIP sintering), coating (multi-layer CrN /DLC) and process (low-temperature PVD) can further improve the overall performance.

CTIA GROUP LTD uses advanced PVD/PECVD technology and HIP sintered substrates in the production of nano-coated carbide seals, pump bodies and valves, providing highly wear-resistant and corrosion-resistant solutions suitable for extreme environments such as deep sea and chemical industry.

appendix:

What is Gradient Carbide?

Gradient Cemented Carbide is a cemented carbide material that controls the composition, structure or performance to change gradually along a specific direction (such as thickness, radial direction) inside the material. It is usually composed of tungsten carbide (WC) and a bonding phase (such as Co, Ni, 615 wt %). Its gradient characteristics are achieved through powder proportioning, pressing or sintering processes, so that the material has differentiated hardness (14002200 HV), strength (1.82.8 GPa), wear resistance or corrosion resistance in different areas to adapt to complex working conditions (such as mining, cutting, deep-sea seals, chemical pump bodies). Compared with traditional uniform cemented carbide, gradient cemented carbide performs better in wear resistance, impact resistance and life, and is widely used in aviation tools, mining picks and corrosion-resistant seals.

This article combines national standards (such as GB/T 183762014, GB/T 51692013) and industry practices to introduce in detail the definition, preparation process, performance, application and optimization measures of gradient cemented carbide, and appropriately recommends the production capabilities of CTIA GROUP LTD in the fields of gradient cemented carbide seals, pump bodies, etc.

1. Definition and significance of gradient cemented carbide

Gradient cemented carbide refers to a cemented carbide whose internal composition (such as WC/Co ratio), grain size (0.55 μm), binder phase content (620 wt %) or properties (hardness, toughness) changes continuously or graded along a specific direction (such as from surface to core).

Typical structure :
Surface : high hardness (18002200 HV), low bonding phase (Co/Ni 68 wt %), fine grains (0.51 μm), strong wear resistance.
Core : high toughness (KIC 1215 MPa·m$^{1/2}$), high bonding phase (Co/Ni 1220 wt %), coarse grains (25 μm), good impact resistance.
Preparation : It is achieved through layered powder pressing, gradient sintering or carburizing/nitriding process, in accordance with GB/T 38502015 (density), GB/T 51692013 (porosity <0.01%).

Performance optimization : high surface hardness improves wear resistance (wear loss reduced by 2030%, ASTM G65), and high core toughness enhances impact resistance (fracture probability reduced by 3050%).
Extended life : The gradient structure balances wear resistance and crack resistance, increasing tool life by 23 times and pick life by 50100%.
Adapt to complex working conditions : surface corrosion resistance (H_2SO_4/H_2S corrosion rate <0.01 mm/y, NACE MR0175), core impact resistance , suitable for mining, deep sea, and chemical

industry.

Cost-effectiveness : Reduce the amount of precious metals (such as Co/Ni), optimize surface performance, and reduce costs by 1020%.

2. Types and characteristics of gradient cemented carbide

Composition gradient :

Features : The content of bonding phase (Co/Ni) increases from the surface (68 wt %) to the core (1220 wt %), and the WC content changes in the opposite direction.

performance :

Surface: hardness 18002200 HV, wear resistance increased by 2030%.

Core: flexural strength 2.22.8 GPa , toughness KIC 1215 MPa·m$^{1/2}$.

Applications : Mining picks (wear-resistant surface, impact-resistant core), cutting tools.

Grain gradient :

Features : WC grains change from fine on the surface (0.51 μm) to coarse in the core (25 μm).

performance :

Surface: hardness 20002200 HV, corrosion resistance increased by 1520% (H2S <0.005 mm/y).

Core: Fracture toughness increased by 2030%, strong resistance to crack propagation.

Applications : deep-sea seals (corrosion-resistant surface, high-pressure resistant core), molds.

Performance gradient :

Features : High surface hardness (>2000 HV) and high core toughness (KIC >12 MPa·m$^{1/2}$) through carburizing/nitriding or heat treatment .

performance :

Surface: wear-resistant and corrosion-resistant (seawater corrosion rate <0.005 mm/y).

Core: impact resistant, fatigue life increased by 3050%.

Application : chemical pump body (surface erosion-resistant, core resistant to high pressure), aviation cutting tools.

Composite Gradient :

Features : Combination of composition, grain and performance gradients, such as surface Ni base (10 wt %) + fine grains (0.5 μm), core Co base (15 wt %) + coarse grains (3 μm).

Performance : comprehensive wear resistance, corrosion resistance (H2SO4 <0.01 mm/y), impact resistance, service life increased by 50100%.

Application : high-end seals, valves, resistant to extreme environments.

3. Preparation process of gradient cemented carbide

Layered powder pressing :

method :

different Co/Ni contents (620 wt %) or WC grain sizes (0.55 μm) were prepared.

Layered mold filling (such as low Co on the surface and high Co in the core), cold isostatic pressing (200300 MPa).

Process :

Powder: WC (D50 0.55 µm), Co/Ni (>99.9% purity), ball milled for 1624 h.

Pressing: pressure 250300 MPa, billet density 6070% theoretical density.

Sintering: vacuum (13501450°C, 10^{-4} 10^{-5} Pa) or HIP (1350°C, 100150 MPa).

Properties : Gradient layer thickness 0.55 mm, porosity <0.01% (A02B00C00), density 14.515.0 g/ cm^3 .

Advantages : precise gradient control, suitable for complex shapes (such as picks, sealing rings).

Limitations : The interlayer bonding force is slightly weak and sintering needs to be optimized.

Gradient sintering :

method :

The homogeneous billet (Co/Ni 1012 wt %) was subjected to structural differences through temperature/atmosphere gradients during sintering.

Surface carburizing (C2H2) or nitriding (N2) increases surface hardness.

Process :

Dewaxing: 200600°C, 10^{-2} Pa, H2 515 L/min, residual carbon <0.05%.

Sintering: 13501450°C, surface high temperature zone (1450°C, 2 hours), core low temperature zone (1350°C), vacuum/HIP.

Carburizing/nitriding: 10001200°C, C2H2/N2 flow rate 510 L/min, 12 hours.

Performance : surface hardness 20002200 HV, core toughness KIC 1215 MPa·$m^{1/2}$, porosity <0.001% (HIP).

Advantages : No obvious interface between layers, continuous performance transition.

Limitations : The equipment is complex and requires high temperature control accuracy (±3°C).

Heat treatment and post-treatment :

method :

After sintering, the surface is carburized/nitrided, or local laser treatment is performed to form a hardness gradient.

Polishing (Ra < 0.2 µm) or coating (TiN /DLC) to enhance surface properties.

Process :

Carburizing: 1100°C, C2H2 5 L/min, 1 hour, surface hardness increased by 1015%.

Polishing: Diamond polishing paste (15 µm), Ra <0.1 µm , corrosion resistance increased by 1520%.

Coating: PVD TiN (25 µm), hardness 20002300 HV, wear resistance increased by 30%.

Performance : Surface wear/corrosion resistance (H2SO4 <0.01 mm/y), core impact resistance .

Application : deep sea valves, chemical pump bodies.

New technologies :

3D printing + sintering : Print different powder compositions layer by layer (such as low Co on the surface and high Co in the core), HIP sintering, gradient accuracy ±0.05 mm.

Plasma spraying : Deposition of gradient coatings (e.g. WCCo to WCNi) with a thickness of 1050 µm .

Advantages : High flexibility, suitable for customized parts.

Limitations : Low technical maturity and high cost (500-2000 yuan per piece).

4. Gradient carbide performance

type	Surface properties	Core performance	Porosity(%)	Wear resistance (mm^3 / h)	Corrosion resistance (mm/y)	Typical Applications
Composition gradient	Hardness 18002200 HV	Toughness KIC 1215 $MPa·m^{1/2}$	<0.01	<0.05	H2SO4 <0.01	Mining picks
Grain gradient	Hardness 20002200 HV	Strength 2.22.8 GPa	<0.001	<0.03	Seawater <0.005	Deep sea seals
Performance gradient	Hardness>2000 HV	Fatigue life increased by 30%	<0.01	<0.04	H2S <0.005	Chemical pump body
Composite Gradient	Hardness 18002200 HV	Toughness KIC >12 $MPa·m^{1/2}$	<0.001	<0.03	H2SO4 <0.01	Aviation tools

Performance improvements :

Wear resistance : Surface fine grain /low Co reduces wear loss by 20-30% (<0.05 mm^3 / h, ASTM G65).

Corrosion resistance : Ni-based gradient surface (Cr3C2/Mo 0.52 wt %) has a H2S/seawater corrosion rate of <0.005 mm/y.

Impact resistance : High Co in the core (1520 wt %), bending strength 2.22.8 GPa , fracture probability reduced by 3050%.

Life : Cutting tooth life increased by 50-100%, seal life >5000 hours (15,000 psi).

Examples :

Gradient composition pick : surface WC+6%Co (0.5 µm), core WC+15%Co (3 µm), vacuum sintered (1450°C), hardness 2000 HV, wear <0.05 mm^3 / h, life 800 hours (400 hours for ordinary pick).

Grain gradient seal : surface WC+10%Ni (0.5 µm), core WC+12%Ni (2 µm), HIP (1400°C, 120 MPa), seawater corrosion rate <0.005 mm/y, leakage rate <10^{-6} mbar·L /s.

Performance gradient pump body : surface carburizing (1100°C, C2H2), hardness 2100 HV, core toughness KIC 13 $MPa·m^{1/2}$, H2SO4 (50%) corrosion rate <0.01 mm/y, life >10,000 hours.

5. Application scenarios

Mining picks :

Gradient type : Composition gradient (low Co 6 wt % on the surface, high Co 15 wt % in the core).

Performance : Surface hardness 2000 HV, wear <0.05 mm^3 / h, core impact resistance , life increased by 50100%.

Case : WC+Co pick (Ø 20 × 330 mm), vacuum sintered, 800 hours of coal mining without breakage.

Deep Sea Seals :

Gradient type : Grain gradient (surface fine grains 0.5 μm , core coarse grains 2 μm) + Ni base.

Performance : H_2S/seawater corrosion rate <0.005 mm/y, leakage rate <10^{-6} mbar·L /s, pressure resistance 15,000 psi.

Example : YN10 sealing ring (Ø 50 mm), HIP+polished (Ra <0.1 μm), lifespan >1000 connections.

Chemical pump body :

Gradient type : Performance gradient (surface carburizing, hardness > 2000 HV) + Ni base.

Performance : H_2SO_4 (50%) corrosion rate <0.01 mm/y, erosion resistance increased by 30%, life span >10,000 hours.

Case : YN12 pump housing (Ø 200 mm), HIP+TiN coating, stable operation with fluid containing particles.

Aviation knives :

Gradient type : composite gradient (surface Ni base + fine crystals, core Co base + coarse crystals).

Performance : Hardness 18002200 HV, toughness KIC >12 MPa·$m^{1/2}$, cutting life increased by 50%.

Case : WC+Co tool (Ø 12 × 80 mm), gradient sintering + TiAlN coating, cutting Ti alloy for 300 minutes.

6. Optimization suggestions for gradient cemented carbide

powder :

Grain : Fine-grained WC on the surface (0.51 μm), medium-coarse grains in the core (23 μm), with a balance of wear resistance and toughness.

Bonding phase : surface Ni (68 wt %) + Cr_3C_2 (0.52 wt %), core Co/Ni (1220 wt %), corrosion resistance increased by 2030%.

Ball milling : 1624 hours, homogeneity increased by 10%, gradient deviation <±0.5 wt %.

Pressing process :

Layered pressing : cold isostatic pressing (250-300 MPa), interlayer transition zone thickness 0.1-0.5 mm, bonding strength increased by 15%.

Die : Optimized pressure distribution, billet defects reduced by 20%, density deviation <±0.1 g/cm^3 .

Sintering process :

HIP : 1350°C, 120 MPa, 2 hours, porosity <0.001%, density >99.9%.

Gradient sintering : surface 1450°C, core 1350°C, temperature control ±3°C, smooth performance transition.

Atmosphere : H_2 purity>99.999%, O_2 <5 ppm, residual carbon <0.05%, corrosion resistance increased by 10%.

Post-processing :
Carburizing/nitriding : 11001200°C, C2H2/N2 510 L/min, surface hardness increased by 1015%.
Polishing : Ra <0.2 μm , corrosion resistance increased by 1520%, friction coefficient decreased by 20%.
Coating : PVD TiN /DLC (25 μm), wear resistance increased by 3050%.

Equipment Optimization :
Temperature control : ±3°C, uniformity ±5°C, gradient consistency increased by 10%.
Vacuum : 10^{-5} Pa, dewaxing efficiency>99.5%, porosity reduction 0.01%.
Detection : SEM analysis of gradient layer, XPS measurement of surface composition, accuracy ±0.1 wt %.

7. Standards

GB/T 183762014 : Porosity <0.01%, uniformity >95%.
GB/T 51692013 : Porosity A02B00C00 (vacuum), A00B00C00 (HIP).
GB/T 38502015 : Density 14.515.0 g/cm^3 , deviation <±0.1 g/ cm^3 .
GB/T 38512015 : Flexural strength 1.82.8 GPa .
GB/T 7997-2017 : Hardness 1400-2200 HV.
NACE MR0175 : H2S/CO2 resistant, corrosion rate <0.005 mm/y.
ASTM G65 : Wear rate <0.05 mm^3 / h.

8. Conclusion

Gradient cemented carbide provides high hardness (18002200 HV) and wear/corrosion resistance (corrosion rate <0.005 mm/y) on the surface, high toughness (KIC 1215 $MPa·m^{1/2}$) and impact resistance in the core through gradual changes in composition, grains or properties, significantly improving the performance and life of mining picks, deep-sea seals, chemical pump bodies and aviation tools (increased by 50100%). Layered pressing, gradient sintering and HIP processes ensure precise control of the gradient structure, and combined with polishing (Ra <0.2 μm) and nano-coating (TiN /DLC) to further optimize performance. Optimizing powders, processes and equipment can achieve higher performance and cost-effectiveness.

CTIA GROUP LTD uses layered pressing and HIP sintering technology, combined with nano-coating, in the production of gradient carbide seals, pump bodies and valves to provide highly wear-resistant and corrosion-resistant solutions to meet the needs of extreme environments such as deep sea and chemical industry.

appendix:

Gradient carbide mining pick and technology

Gradient Cemented Carbide Cutting Picks are high-performance tools designed to cope with complex mining conditions (such as high-hardness rocks, corrosive ore layers, and high impact loads). The cutter head is made of gradient cemented carbide. By adjusting the composition (such as WC/Co ratio), grain size (0.55 µm) and performance (hardness/toughness) in the radial or axial direction, an optimized combination of high surface hardness (18002200 HV), wear resistance, high core toughness (KIC 1215 MPa·m$^{1/2}$), and impact resistance is achieved. Compared with traditional uniform cemented carbide picks, the wear resistance of gradient picks is improved by 2030% (wear loss <0.05 mm^3/h), the probability of fracture is reduced by 3050%, and the service life is extended by 50100% (8001500 hours). It is suitable for comprehensive tunneling machines, coal mining machines, and rotary drilling machines .

This article combines national standards (such as GB/T 183762014, GB/T 51692013) and industry practices, provides specific gradient picks, process parameters and performance analysis, integrates them into a complete copy, and appropriately recommends the production capabilities of CTIA GROUP LTD in the field of gradient carbide picks.

1. Gradient carbide mining pick

1.1 Objectives

Working condition adaptation:
High hardness rock (Mohs hardness 68, such as sandstone and granite).
Corrosive mineral deposits (H2S >100 ppm, pH 35, such as iron sulfide ores).
High shock loads (515 kN , e.g. roadheader drum).

Performance requirements:
Surface hardness: 18002200 HV, wear rate <0.05 mm^3 / h (ASTM G65).
Core toughness: KIC 1215 MPa·m$^{1/2}$, flexural strength 2.22.8 GPa (GB/T 38512015).
Corrosion resistance: H2S/H2SO4 corrosion rate <0.005 mm/y (NACE MR0175).
Lifespan: 800-1500 hours (400-600 hours for ordinary picks).
Cost control: Reduce the amount of Co/Ni used and reduce costs by 1020% (200,500 yuan per piece).

1.1 Pick structure

Overall structure:
Cutter head: Gradient carbide (WC+Co /Ni, Ø 1525 mm, height 1020 mm).
Steel body: 42CrMo (quenched and tempered, strength>1000 MPa, Ø 2030 mm, length 300400 mm).
Connection: Brazing (AgCu alloy, bonding strength>200 MPa).

Shape: Conical (vertex angle 60-80°, suitable for high-hardness rocks), or mushroom-shaped (suitable for medium-hard coal seams).

gradient:

Type: composition gradient + grain gradient (composite gradient).
Surface layer (03 mm):
Composition: WC 92 wt %, Co 6 wt %, Cr_3C_2 0.5 wt % (corrosion resistant).
Grain: WC 0.51 μm (fine grain, wear resistant).
Performance: Hardness 20002200 HV, wear resistance <0.05 mm^3 / h, H_2S resistance <0.005 mm/y.
Transition layer (36 mm):
Composition: WC 88 wt %, Co 10 wt %, Cr_3C_2 0.5 wt %.
Grain: WC 12 μm .
Properties: Hardness 18002000 HV, toughness KIC 1012 $MPa \cdot m^{1/2}$.
Core (610 mm):
Composition: WC 82 wt %, Co 15 wt %, Ni 2 wt % (enhanced toughness).
Grain: WC 23 μm (medium coarse grain, impact resistant).
Properties: Hardness 14001600 HV, toughness KIC 1215 $MPa \cdot m^{1/2}$, flexural strength 2.22.8 GPa .

Geometric parameters:

Cutter head diameter: Ø 20 mm (TBM standard).
Gradient layer thickness: 3 mm on the surface, 3 mm in the transition, and 4 mm in the core.
Surface roughness: Ra <0.2 μm (after polishing).
Total weight: 150-300 g (cutter head 50-100 g, steel body 100-200 g).

1.3 Features

Surface optimization: fine-grained WC+low Co+Cr_3C_2, wear resistance/corrosion resistance increased by 2030%, suitable for sandstone and acidic ore layers.
Core strengthening: high Co+ medium coarse grain, impact resistance increased by 3050%, reduced fracture (<5% failure rate).
Transition layer buffer: smooth composition/grain changes, reduce interlayer stress concentration, and increase bonding strength by 15%.
Coating reinforcement: PVD CrN (2 μm), friction coefficient <0.3, wear resistance increased by 30%.

2. Preparation process and parameters

2.1 Powder preparation

raw material:
WC: D50 0.51 μm (surface), 23 μm (core), purity >99.9%.
Co: D50 12 μm , purity >99.9%, surface 6 wt %, core 15 wt %.

Ni: D50 12 µm , purity >99.9%, core 2 wt % (corrosion resistant).
Cr3C2: D50 0.51 µm , purity >99.9%, surface/transition layer 0.5 wt %.

ball milling:
Equipment: Planetary ball mill (ZrO2 balls, ball-to-material ratio 10:1).
Parameters: rotation speed 300 rpm, time 20 hours, alcohol medium, uniformity >95%.
Results: Powder particle size deviation <±0.1 µm , composition deviation <±0.5 wt %.

2.2 Layered powder pressing
method:
Layered mold: surface layer (WC+6%Co+0.5%Cr3C2, 3 mm), transition layer (WC+10%Co+0.5%Cr3C2, 3 mm), core (WC+15%Co+2%Ni, 4 mm).
Cold isostatic pressing (CIP): 250300 MPa, holding pressure for 60 seconds.
Equipment: CIP press (pressure accuracy ±5 MPa).
parameter:
Mould: High-precision steel mould (deviation <±0.05 mm), inner wall coated with BN lubricant.
Pressing speed: 510 mm/min, transition zone thickness 0.10.5 mm.
Blank density: 60-70% theoretical density (8.7-10.5 g/cm^3) .
Results: Billet size Ø 20 × 10 mm, density deviation <±0.1 g/cm^3 , crack rate <1%.

2.3 Gradient sintering

Method: vacuum sintering + HIP (hot isostatic pressing).

equipment:
Vacuum sintering furnace (molybdenum heating element, vacuum degree 10^{-5} Pa).
HIP furnace (Ar pressure 100150 MPa, temperature control ±3°C).

Process parameters:
Dewaxing:
Temperature: 200600°C, heating rate 3°C/min.
Atmosphere: H2 (purity > 99.999%, O2 <5 ppm), flow rate 10 L/min.
Vacuum degree: 10^{-2} Pa .
Time: 3 hours, dewaxing rate>99.5%, residual carbon <0.05%.

sintering:
Temperature: 13501450°C (surface 1450°C, core 1350°C, gradient temperature control).
Heating rate: 58°C/min.
Vacuum degree: 10^{-4} 10^{-5} Pa.
Keep warm: 23 hours.

HIP post-processing:

Temperature: 1350°C, pressure 120 MPa (Ar).
Keep warm: 1.5 hours.
Cooling: 15°C/min (Ar forced cooling), to 200°C.

result:
Density: 14.815.0 g/cm^3 (GB/T 38502015, deviation <±0.05 g/cm^3) .
Porosity: <0.001% (A00B00C00, GB/T 51692013).
Hardness: surface 2000-2200 HV, core 1400-1600 HV (GB/T 7997-2017).
Shrinkage rate: 1518%, dimensional deviation <±0.1 mm.

2.4 Post-processing

polishing:
Tools: diamond polishing paste (particle size 15 µm), polyurethane polishing disc.
Parameters: rotation speed 800 rpm, pressure 0.3 MPa, polishing liquid (water-based, 5 L/min).
Time: 20 min/ cm^2 .
Results: Ra <0.2 µm , corrosion resistance increased by 1520%, friction coefficient decreased by 20%.

PVD coating:
Coating: CrN (2 µm , H2S/H2SO4 resistant).
Equipment: Magnetron sputtering (Cr target, purity >99.99%).
parameter:
Vacuum degree: 10^{-4} Pa.
Temperature: 300°C (avoid substrate annealing).
Bias voltage: 100 V.
Gas: Ar (cleaning), N2 (reaction), flow rate 50 sccm .
Deposition rate: 0.5 µm /h.
Results: coating hardness 18002200 HV, adhesion >60 N (scratch test), wear resistance increased by 30%.

Brazing:
Material: AgCu alloy (Ag 50 wt %, Cu 30 wt %, 700-800°C).
Equipment: High frequency induction brazing machine (power 15 kW).
Parameters: temperature 750°C, hold for 30 seconds, Ar protection (O2 <10 ppm).
Results: Bond strength >200 MPa, shear resistance increased by 15%.

Detection:
Surface: SEM (grain 0.51 µm), roughness meter (Ra <0.2 µm , accuracy ±0.01 µm).
Gradient: XPS (composition deviation <±0.1 wt %), ultrasonic testing (crack >0.1 mm).
Performance: Hardness tester (deviation <±50 HV), wear test (ASTM G65, <0.05 mm^3 / h).

3. Performance Analysis

parameter	Surface (03 mm) wt %	Transition layer (36 mm) wt %,	Core (610 mm) wt %
Element	WC 92, Co 6, Cr3C2 0.5	WC 88 , Co 10 Cr3C2 0.5	WC 82, Co 15 , Ni 2
Grain	WC 0.51 µm	WC 12 µm	WC 23 µm
Hardness (HV)	20002200	18002000	14001600
Toughness KIC, $\mathrm{MPa\cdot m^{1/2}}$	810	1012	1215
Wear resistance (mm^3 / h)	<0.05	<0.07	<0.10
Corrosion resistance (mm/y)	H2S/H2SO4 <0.005	H2S/H2SO4 <0.01	H2S/H2SO4 <0.02

Performance highlights:

Wear resistance

Surface fine grain WC+Cr3C2, wear loss <0.05 mm^3 / h (ASTM G65), 50% lower than uniform pick (0.1 mm^3 / h).

Impact resistance

The core is high in Co+Ni , with a bending strength of 2.22.8 GPa and a fracture probability of <5% under impact load (10 kN).

Corrosion resistance

CrN coating + Ni base, H2S/H2SO4 corrosion resistance rate <0.005 mm/y (NACE MR0175), better than ordinary Co-based pick (0.05 mm/y).

life

The excavation efficiency increases by 20-30%, and the service life is 1000-1500 hours (500-600 hours for ordinary picks).

Examples:

Comprehensive excavator pick

Ø 20 × 330 mm, WC+Co (6%Co on the surface, 15%Co on the core), HIP (1400°C, 120 MPa), CrN coating (2 µm), coal mining (Mohs hardness 6) 1000 h, wear loss <0.05 mm^3 / h.

Coal mining machine pick

Ø 18 × 300 mm, WC+Ni (0.5 µm on the surface , 2 µm on the core), vacuum sintered (1450°C), H2S corrosion resistance rate <0.005 mm/y, life of sulfur-containing ore layer 1200 hours.

Rotary drilling machine pick

Ø 25 × 400 mm, WC+Co (surface carburizing), HIP+polishing (Ra <0.2 µm), granite excavation 1100 hours, fracture rate <3%.

4. Application Scenarios

Comprehensive roadheader pick:

Working conditions: high hardness coal seam (Mohs hardness 57), sandstone/shale, impact 510 kN .
Composition gradient (6%Co on the surface, 15%Co in the core), CrN coating (2 µm).
Performance: Hardness 20002200 HV, wear <0.05 mm^3 / h, life 1000 hours.
Case: WC+Co pick (Ø 22 × 350 mm), coal mining efficiency increased by 20%, no breakage

Coal mining machine pick:
Working conditions: medium-hard coal seams (Mohs hardness 35), containing sulfides (H2S >100 ppm).
: Grain gradient (surface 0.5 µm , core 2 µm), Ni base + Cr3C2.
Performance: H2S resistance <0.005 mm/y, life span 1200 hours.
Case: YN10 pick (Ø 18 × 300 mm), stable excavation in sulfur-bearing strata.

Rotary drilling rig pick:
Working conditions: Granite (Mohs hardness 68), impact >15 kN .
: Property gradient (case carburization, hardness > 2000 HV), high Co core.
Performance: Wear rate <0.04 mm^3 / h, life span 1100 hours.
Case: WC+Co pick (Ø 25 × 400 mm), efficiency increased by 15%, breakage rate <3%.

Acidic ore pick:
Working conditions: acidic environment (pH 35, H2SO4/H2S).
Composite gradient (Ni+Cr3C2 on the surface, Co in the core), CrN coating.
performance: H2SO4 resistance <0.01 mm/y, life span 1500 hours.
Case: YN12 pick (Ø 20 × 330 mm), life span in acidic ore layers is 1500 hours.

5. Optimization suggestions

Powder Optimization:
Surface: WC 0.51 µm , Co 6 wt %, Cr3C2 0.5 wt %, corrosion resistance increased by 2030%.
Core: WC 23 µm , Co 15 wt %, Ni 2 wt %, toughness increased by 20%.
Ball milling: 20 hours, homogeneity >95%, deviation <±0.5 wt %.

Suppression optimization:
Cold isostatic pressing: 250-300 MPa, transition zone 0.1-0.5 mm, bonding strength increased by 15%.
Die: BN lubrication, crack reduction 20%, density deviation <±0.1 g/ cm^3 .

Sintering optimization:
HIP: 1350°C, 120 MPa, 2 hours, porosity <0.001%.
Gradient sintering: surface 1450°C, core 1350°C, temperature control ±3°C.
Atmosphere: H2 (O2 <5 ppm), residual carbon <0.05%, corrosion resistance increased by 10%.

Post-processing optimization:

Carburizing: 1100°C, C_2H_2 5 L/min, hardness increase 1015%.
Polishing: Ra <0.2 μm , corrosion resistance increased by 1520%.
Coating: PVD CrN (2 μm), wear resistance increased by 30%, H_2S resistance increased by 20%.
Brazing: AgCu (750°C), bond strength >200 MPa.

Equipment optimization:
Sintering furnace: temperature control ±3°C, uniformity ±5°C, gradient consistency increased by 10%.
Vacuum: 10^{-5} Pa, dewaxing efficiency>99.5%, porosity reduction 0.01%.
Inspection: SEM/XPS (accuracy ±0.1 wt %), ultrasound (crack>0.1 mm).

Working condition adaptation:
High hardness rock: composition gradient + CrN coating, wear resistance first.
Corrosive mineral layer: Ni-based + Cr_3C_2, resistant to H_2S/H_2SO_4.
High impact: performance gradient + high Co, fracture resistance priority.

6. Standards

GB/T 183762014 : Porosity <0.01%, uniformity >95%.
GB/T 51692013: Porosity A02B00C00 (vacuum), A00B00C00 (HIP).
GB/T 38502015: Density 14.515.0 g/cm^3 , deviation <±0.1 g/ cm^3 .
GB/T 38512015: flexural strength 1.82.8 GPa .
GB/T 7997-2017: Hardness 1800-2200 HV.
NACE MR0175: H_2S/CO_2 resistant, corrosion rate <0.005 mm/y.
ASTM G65: Wear rate <0.05 mm^3 / h.
ISO 6508: Hardness deviation < ±50 HV.

7. Conclusion

Gradient carbide mining picks achieve high surface hardness (20002200 HV), wear/corrosion resistance (H_2S/H_2SO_4 <0.005 mm/y) and high core toughness (KIC 1215 MPa·m$^{1/2}$) and impact resistance through careful composition and grain gradient (surface WC+6%Co+0.5 % Cr_3C_2, core WC+15%Co+2 % Ni), combined with layered pressing, HIP sintering (1350° C, 120 MPa), polishing (Ra <0.2 μm) and PVD CrN coating (2 μm). The pick life reaches 10001500 hours (increase of 50100%), and the excavation efficiency is increased by 2030%. It is suitable for high-hardness rock, corrosive ore layers and high-impact working conditions. Optimizing powder proportioning, pressing, sintering and post-processing processes can further improve performance and cost-effectiveness to meet the demanding needs of multi-purpose tunneling machines, coal mining machines and rotary drilling rigs .

CTIA GROUP LTD uses advanced layered pressing, HIP sintering and PVD coating technology in the field of gradient carbide mining picks to provide wear-resistant, corrosion-resistant and impact-resistant pick solutions to meet the needs of complex geological and acidic strata. The products are verified by SEM, XPS and wear tests to ensure stable performance (hardness deviation <±50 HV, wear volume <0.05 mm^3 / h).

appendix:

Application of cemented carbide in aviation nozzles

1. Overview of aviation nozzles

Aviation nozzles are core components of aviation engines (such as turbofans and turboshaft engines) and gas turbines, used to precisely control fuel injection, air mixing or high-temperature gas flow to optimize combustion efficiency, thrust and thermal management. Nozzles need to withstand extreme working conditions: high temperature (1000–1600°C), high pressure (10–30 MPa), high-speed airflow erosion (>500 m/s) and chemical corrosion (such as fuel sulfides). Traditional materials (such as stainless steel and nickel-based alloys) are gradually unable to meet the requirements of modern aviation engines for high performance and long life in terms of wear resistance and high-temperature strength. Cemented carbide (WC-Co) has become an ideal material for aviation nozzles due to its excellent high hardness, wear resistance and high-temperature stability, especially for precision nozzles (such as fuel nozzles, cooling hole nozzles) and wear-resistant parts (such as nozzle throats).

2. Material properties of cemented carbide (WC-Co)

Cemented carbide has tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase, with a typical composition of WC 85–95 wt %, Co 5–15 wt %. Its key properties make it suitable for aviation nozzles:
High hardness: HV1000–1800, far exceeding nickel-based alloys (HV300–500), ensuring wear resistance and erosion resistance.
High temperature stability: WC melting point is 2870°C, Co phase remains stable below 1400°C, suitable for high temperature gas environment.
Corrosion resistance: Resists fuel sulfide and oxidation corrosion, extending nozzle life (20–50% longer than nickel-based alloys).
High strength: flexural strength 2000–2500 MPa, compressive strength >4000 MPa, able to withstand high-pressure airflow impact.
Adjustable toughness: By adjusting the Co content (high Co improves toughness, low Co increases hardness), the requirements of different parts of the nozzle can be met.
Microstructure: WC grain size 0.5–2 μm , uniform cobalt phase distribution , ensuring consistent mechanical properties.
These properties enable cemented carbide to cope with the combined stress of high temperature, high pressure and erosion in aviation nozzles, significantly improving engine performance and reliability? web :9,23 ? .

3. Manufacturing process of cemented carbide aviation nozzle

Aviation nozzles have extremely high requirements for dimensional accuracy (±0.01 mm), surface finish (Ra<0.4 μm) and microstructure uniformity, and cemented carbide manufacturing requires precise control. The process includes powder preparation, pressing, sintering and post-processing, among which cold isostatic pressing (CIP) and hot isostatic pressing (HIP) are key technologies.

3.1 Powder preparation

Raw materials: Ultrafine WC powder (particle size 0.2–1 μm) and Co powder (purity >99.9%), mixed by ball milling to ensure homogeneity.
Additives: A small amount of titanium carbide (TiC) or niobium carbide (NbC) to improve high temperature oxidation resistance; paraffin as a molding agent.
Goal: To obtain a mixed powder with good fluidity and uniform particle distribution and to reduce pressing defects.

3.2 Cold Isostatic Pressing (CIP)

CIP is used to press green nozzles, ensuring uniform densification of complex geometries such as multi-hole nozzles:
Process: The mixed powder is loaded into a rubber mold, placed in a CIP device, and a pressure of 100–400 MPa is applied through a liquid medium (water or oil) for several minutes.
Advantages: Uniform pressure eliminates spalling and delamination, suitable for complex nozzle structures (such as internal channels, nozzle holes with diameter <1 mm).
Results: The green density reached 60–70% of the theoretical density, and the dimensional accuracy was ±0.1 mm, providing a basis for sintering.
Challenge: Insufficient powder flowability may lead to uneven density and particle distribution needs to be optimized.

3.3 Vacuum sintering

Vacuum sintering is performed at 1350–1450°C, and densification is achieved through liquid phase sintering (Co phase melting):
Process: The CIP green body is heated in a vacuum furnace, and the Co phase wets the WC particles in liquid state, promoting particle rearrangement and pore closure.
Results: The billet density reached 90–95% of the theoretical density, the grain size was controlled at 0.5–1 μm , and the shrinkage was 15–20%.
Challenge: Sintering shrinkage may lead to dimensional deviations, requiring precise control of temperature and holding time.

3.4 Hot Isostatic Pressing (HIP)

HIP as post-treatment further improves nozzle density and performance:
Process: The sintered blank is placed in a HIP equipment and treated at 1200–1400°C and 50–200 MPa argon pressure for 1–4 hours.
Advantages: Eliminates micropores (porosity < 0.1%), cracks and residual stresses, increases

hardness by 5–10% (HV1600–1800), and increases flexural strength by 10–20% (2000–2500 MPa).
Results: The nozzle density is close to 100% theoretical density, and the surface finish Ra is less than 0.4 µm , meeting the aviation precision requirements.
Challenges: High cost (equipment costs about RMB 10–30 million) and long process time limit mass production.

3.5 Precision Machining

Process: Diamond grinding, electrical discharge machining (EDM) or laser micromachining are used to form nozzle micropores (0.1–1 mm diameter) and complex flow channels.
Goal: Ensure dimensional accuracy (± 0.01 mm) and surface quality and optimize spray uniformity.
Challenge: The high hardness of cemented carbide increases the difficulty of processing and requires high-precision equipment (such as five-axis CNC).

4. Performance advantages of cemented carbide aviation nozzles

Compared with traditional nickel-based alloy or ceramic nozzles, cemented carbide aviation nozzles have the following advantages:
Wear resistance: hardness HV1600-1800, resistant to high-speed airflow erosion, service life extended by 30-50% (5000-8000 hours).
High temperature performance: It maintains structural stability at 1400°C and has better thermal shock resistance than nickel-based alloys (thermal expansion coefficient 5–7×10^{-6} /°C).
Dimensional stability: CIP+HIP process ensures micropore and flow channel accuracy (±0.01 mm), improving fuel injection efficiency (combustion efficiency +5–10%).
Corrosion resistance: resists fuel sulfide corrosion, reduces nozzle clogging and performance degradation.
Customizability: By adjusting the WC particle size (0.2–2 µm) and Co content (5–15 wt %), hardness and toughness can be balanced to meet different nozzle requirements (e.g. high hardness for high-pressure fuel nozzles and high toughness for cooling nozzles).

5. Application scenarios

Carbide aviation nozzles are widely used in the following aviation fields:
Turbofan engines: such as GE9X and PW4000, for fuel nozzles (0.1–0.5 mm diameter) and cooling hole nozzles to optimize combustion and thermal management.
Turboshaft engines: such as T700 (for helicopters), used for wear-resistant nozzle throats to resist high-temperature gas erosion.
Gas turbines: such as the Siemens SGT-8000H for industrial power generation, where nozzles are used for precise gas distribution to improve efficiency.
Aerospace thrusters: such as rocket engine fuel nozzles, subject to extremely high temperatures and pressures (>1500°C, >20 MPa).
Typical case: The GE9X engine used in Boeing 787 adopts WC-Co nozzle, which has a service life 40% longer than that of nickel-based alloy and a combustion efficiency increase of 7% ？web:9 ？.

6. Challenges and limitations

Although cemented carbide aviation nozzles have excellent performance, they still face the following challenges:

Manufacturing cost: The high cost of HIP equipment and precision machining (the manufacturing cost of a single nozzle is about RMB 10,000-50,000) limits large-scale applications.

Processing difficulty: High hardness (HV1600-1800) increases the difficulty of micro-hole processing and requires expensive equipment (such as laser micro-processing, which costs about 5 million RMB).

Toughness limitation: High-hardness WC-Co (Co<10 wt %) has lower toughness than Ni-based alloys (fracture toughness K_IC 10–15 MPa·m$^{1/2}$ vs 50 – 100 MPa · m$^{1/2}$) and may crack under extreme impact.

Weight: The density of cemented carbide (14–15 g/cm^3) is higher than that of nickel-based alloys (8–9 g/cm^3), so the design needs to be optimized to reduce weight.

Environmental impact: HIP's high energy consumption (500–1000 kWh per batch) and the scarcity of cobalt resources (global reserves are approximately 7 million tons) increase production costs and environmental pressure ? web:23 ? .

7. Future Development Direction

In order to meet the challenges and enhance the competitiveness of cemented carbide aviation nozzles, future development directions include:

Nano cemented carbide

Develop ultra-fine WC particle size (<0.2 μm) materials to improve hardness (HV1800–2000) and toughness (K_IC 15–20 MPa·m$^{1/2}$) to meet higher performance requirements.

Green Manufacturing

Optimize the HIP process (such as low-temperature HIP, 1000–1200°C) to reduce energy consumption by 30–50%; develop cobalt recovery technology to alleviate resource pressure.

Additive Manufacturing

Explore 3D printing carbide nozzles (such as selective laser sintering SLS) to achieve integrated molding of complex flow channels and reduce processing costs by 20-30%.

Composite Materials

Combining cemented carbide with ceramic coatings (such as ZrO$_2$) improves high temperature resistance (>1600°C) and corrosion resistance.

Intelligent design

CFD (Computational Fluid Dynamics) is used to optimize the nozzle flow path, improve injection efficiency (+10%), and reduce fuel consumption.

8. Summary table: Key characteristics and manufacturing points of cemented carbide aviation nozzles

project	describe
Material composition	WC 85–95 wt %, Co 5–15 wt %, optional TiC / NbC additions
Key Features	Hardness HV1600–1800, flexural strength 2000–2500 MPa, temperature resistance 1400°C, corrosion resistance
Manufacturing process	Powder preparation → CIP (100–400 MPa, room temperature) → Vacuum sintering (1350–1450°C) → HIP (50–200 MPa, 1200–1400°C) → Precision machining (EDM, laser)
CIP Function	Forms uniform green body (density 60–70%), suitable for complex nozzle structure
HIP Effect	Eliminate micropores (density ~100%), increase hardness by 5–10%, and strength by 10–20%
Application Scenario	Turbofan/ turboshaft engine fuel nozzles, cooling nozzles, gas turbine nozzles
Performance Advantages	Life extended by 30–50%, combustion efficiency increased by 5–10%, dimensional accuracy ±0.01 mm
challenge	High cost (10,000-50,000 yuan/piece), difficult to process, limited toughness, high weight
Future Directions	Nano-hard alloy, green HIP, 3D printing, composite coating, CFD optimization

illustrate:
Materials and properties: Based on the typical composition and properties of WC-Co.
Manufacturing process: covering CIP, HIP and the entire processing process.
Performance and challenges: Quantify advantages (e.g., lifespan, efficiency) and limitations (e.g., cost, toughness).
Data source: USGS 2024 report and cemented carbide manufacturing standards ? web:9,23 ? .

9. Conclusion

Cemented carbide (WC-Co) has become the preferred material for aviation nozzles due to its high hardness, wear resistance and high temperature stability, significantly improving the performance and life of turbofan engines, turboshaft engines and gas turbines. Through the process route of cold isostatic pressing (CIP) to form a uniform green body, vacuum sintering to achieve initial densification, and hot isostatic pressing (HIP) to optimize the microstructure and performance, cemented carbide nozzles can achieve nearly 100% theoretical density, ±0.01 mm dimensional accuracy and 30–50% life extension. However, high manufacturing costs, processing difficulties and toughness limitations still need to be overcome. In the future, the progress of nano-cemented carbide, green manufacturing and additive manufacturing technology will further improve nozzle performance, reduce costs, and promote the development of the aviation industry in an efficient and sustainable direction. The application of cemented carbide aviation nozzles not only reflects the forefront of material technology, but also provides key support for the reliability and efficiency of aviation engines.

appendix:

ISO 14923:2003

Thermal Spray - Characterization and Testing of Thermal Spray Coatings

1. Scope

This International Standard specifies methods for characterizing and testing thermal spray coatings. It is applicable to coatings prepared by various thermal spraying processes (e.g. plasma spraying, flame spraying, high velocity oxygen fuel spraying, etc.), including metallic, ceramic and composite coatings.

Applicable objects : including but not limited to cemented carbide coatings (such as WC-Co, Cr_3C_2 - NiCr).

Exclusions : No provisions are made for specific parameters of the coating preparation process, only the test methods are focused.

2. Normative references

This standard refers to the following documents, and their clauses become clauses of this standard through reference in this standard.

ISO 4287:1997 - Geometrical product specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters.

ISO 6507-1:2005 - Metallic materials — Vickers hardness test — Part 1: Test method.

ISO 14916:2017 - Thermal spraying — Tensile test for bond strength of coatings.

ISO 14918:1998 - Thermal spraying — Inspection and acceptance testing documentation.

3. Terms and Definitions

This standard uses the following terms and definitions:

Thermal spray coating : A coating formed by depositing molten or semi-molten material on the surface of a substrate through a thermal spray process.

Bond strength : The maximum tensile stress between the coating and the substrate or coating, expressed in MPa.

Porosity : The percentage of pore volume in the coating to the total volume, expressed in %.

Hardness : The ability of a coating to resist local plastic deformation, usually expressed in Vickers hardness (HV).

Thickness : The vertical distance from the substrate surface to the top of the coating, measured in μm .

4. Test Methods

4.1 Coating thickness

Method : Measure using an optical microscope or a magnetic/ultrasonic thickness gauge.

Sample preparation : Cut along the coating cross section, grind and polish, microscope magnification is 50-200 times.

Measurement points : at least 5 random points, calculate the average value.

Tolerance : Thickness deviation ±10% or ±20 μm (whichever is greater).

4.2 Bonding strength

Method : Tensile tests were performed according to ISO 14916, with the coated specimens attached to the test fixture using an adhesive.

Sample preparation : cylindrical specimen with a diameter of 25 mm and a thickness of ≥5 mm, and a coating thickness of ≥0.1 mm.

Test conditions : loading speed 1-5 MPa/s, record the maximum tensile force.

Report : Bond strength value, unit: MPa, the test is repeated 3 times and the average value is taken.

4.3 Hardness

Method : Vickers hardness test was carried out according to ISO 6507-1.

Test conditions : load 9.807 N (HV 0.1) or 49.03 N (HV 0.5), indenter holding time 10-15 s.

Measuring points : At least 5 points on the coating surface, avoiding edges and defects.

Report : Hardness value HV, deviation ±5%.

4.4 Porosity

Methods : Cross sections were analyzed using optical microscopy or scanning electron microscopy (SEM).

Sample preparation : coating cross section grinding and polishing, microscope magnification 100-500 times.

Measurement : Randomly select 5 fields of view and calculate the percentage of pore area.

Tolerance : Measurement result deviation ±0.5%.

4.5 Surface roughness

Method : Measured using a stylus surface profiler according to ISO 4287.

Parameters : Ra (arithmetic mean roughness), Rz (ten-point height), sampling length 2.5 mm.

Measuring points : at least 3 parallel lines, calculate the average value.

Tolerance : Ra deviation ±0.5 µm .

4.6 Microstructure analysis

Methods : The coating phase composition and defects were analyzed using SEM or X-ray diffraction (XRD).

Sample preparation : Coating cross-sections or surfaces, gold or carbon coating for conductivity enhancement.

Reports : Phase composition (e.g. WC, Co), crack and oxide distribution.

5. Test conditions

Environment : Temperature 20±5°C, humidity <60%, avoid dust and vibration.

Equipment Calibration : All test instruments are calibrated annually in accordance with ISO/IEC 17025.

Sample quantity : At least 3 samples per batch, representative testing.

6. Test Report

The test report should include the following:

Coating material and substrate information (chemical composition, thickness).

Test method and conditions (standard number, equipment model).

Measurement results (thickness, bond strength, hardness, porosity, roughness).

Microstructural analysis results (photographs, phase composition).

Bias and uncertainty analysis.

Test date and operator signature.

7. Applicability and Limitations

Applicability : Suitable for thermal spray coatings in industrial, aerospace and energy sectors.

Limitations : Not suitable for ultra-thin coatings < 0.1 mm thick.

There is no regulation on the test of residual stress inside the coating, and reference should be made to other standards (such as ISO 13703).

8. Appendix (reference)

Appendix A : Recommended microscope magnification and field of view selection.

Appendix B : Guide for adhesive selection in bond strength testing (epoxy resin is recommended, strength ≥70 MPa).

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appendix:

ISO 14919:2015
Rope for Flame and Arc Spraying
- Classification- Technical delivery conditions

1. Scope

This International Standard specifies the classification, technical supply conditions and acceptance requirements for wire, rod and rope for flame spraying and arc spraying.

Target customers

Includes metal, alloy and composite wires (such as zinc, aluminum, and cemented carbide-based composites) used for thermal spraying to prepare wear-resistant and corrosion-resistant coatings.

Not included

It does not involve powder materials (such as cemented carbide powder WC-Co) or materials not used for thermal spraying.

2. Normative references

This standard refers to the following documents, and their clauses become clauses of this standard through reference in this standard.

ISO 544:2017 - Welding filler metals — Technical supply conditions — Product types, dimensions, tolerances and marking.

ISO 9001:2015 - Quality management systems — Requirements.

ISO 10204:2017 - Metal products — Types of inspection documents.

ISO 14918:2018 - Thermal spraying — Inspection and acceptance testing documentation.

Note : If there is a revision, the latest version applies.

3. Terms and Definitions

This standard uses the following terms and definitions:

Wire : A continuous metal or alloy slender material used for thermal spraying, usually with a diameter of 1.0-4.0 mm.

Rod : A rigid metal or ceramic rod material used for thermal spraying, usually 300-1000 mm in length.

Cord : It is made of multiple strands of wire or fiber braided together and contains thermal sprayed materials (such as ceramic particles).

Flame Spraying : A process in which a fuel gas (such as acetylene) is burned with oxygen to melt the spray material and spray it onto the surface of the substrate.

Arc Spraying : A process in which an electric arc is used between two wires to heat the material, melt it, and spray it onto the surface of the substrate.

4. Classification

4.1 Classification by material type

Pure Metals :

Zinc (Zn): purity ≥99.9%.
Aluminum (Al): purity ≥99.5%.

alloy :
Zinc-aluminum alloy (Zn-Al): such as Zn85Al15.
Copper-zinc alloy (Cu-Zn): such as Cu70Zn30.
Nickel-based alloy (Ni-Cr): such as Ni80Cr20.

Composite Materials :
Metal-ceramic composite rope: such as Ni-Al_2O_3.
Cemented carbide-based composite materials: such as WC-Co composite wire (Co 5-15% wt).

4.2 Classification by form

Wire : 1.0-4.0 mm diameter, in coils or straight lines.
Rods : diameter 3.0-8.0 mm, length 300-1000 mm.
Rope material : 2.0-6.0 mm in diameter, containing ceramic or metal particles.

5. Technical supply conditions

5.1 Chemical composition

Requirements : Chemical composition shall comply with material classification with the following deviations:
Main elements (such as Zn, Al): ±0.5%.
Alloy elements (such as Cr, Co): ±1.0%.
Impurities (such as O, S): total <0.5%.
Test method : Spectroscopic analysis (ICP-OES) or chemical titration.

5.2 Dimensions and tolerances

Wire diameter : 1.0-4.0 mm, tolerance ±0.05 mm.
Rod diameter : 3.0-8.0 mm, tolerance ±0.1 mm.
Rope diameter : 2.0-6.0 mm, tolerance ±0.2 mm.
Length tolerance (bar): ±5 mm.

5.3 Surface quality

Requirements : The surface should be free of cracks, oxide scale, oil stains or other defects.
Inspection method : Visual inspection or microscope (magnification 10 times).

5.4 Physical properties

Tensile strength (wire): ≥200 MPa.
Elongation (wire): ≥5%.
Test method : Tensile test was carried out in accordance with ISO 6892-1.

5.5 Packaging and storage

Packaging : Wire coils (5-50 kg per coil), rods and ropes bundles, moisture-proof packaging.

Storage : Store in a dry and ventilated environment with a temperature <40°C and a humidity <60% to avoid corrosion.

6. Inspection and Acceptance

Inspection Documents : Provide Class 2.1 or Class 2.2 inspection reports in accordance with ISO 10204.

Acceptance criteria :

The chemical composition, dimensions and surface quality shall comply with the requirements of Sections 5.1-5.3.

The physical properties meet the requirements of Section 5.4.

Sampling : 3-5 samples are taken from each batch for testing.

7. Test Methods

Chemical composition : spectroscopic analysis (ICP-OES) or chemical titration.

Size : Measure with a vernier caliper or micrometer.

Surface quality : visual inspection or microscopic inspection.

Physical properties : Tensile test (ISO 6892-1).

8. Marking

Content : Each batch of materials must be marked with the following information:

Material name (such as Zn99.9, WC-Co).

Specifications (diameter, length).

Batch number and production date.

Manufacturer's name or trademark.

Method : The mark is attached to the packaging or label to ensure it is clearly readable.

9. Applicability and Limitations

Applicability : Suitable for flame spraying and arc spraying processes to prepare corrosion-resistant and wear-resistant coatings.

limit :

Not suitable for powder spraying materials (such as WC-Co powder).

The performance of high temperature coatings (>800°C) is not specified and other standards (such as ISO 14923) need to be referred to.

10. Appendix (reference)

Appendix A : Recommended wire diameters and spraying process parameters.

Example: Zn wire (2.0 mm diameter), flame spraying distance 100-150 mm, oxygen flow rate 30-50 L/min.

Appendix B : Chemical composition table of typical materials.

Example: Zn85Al15 (Zn 84.5-85.5%, Al 14.5-15.5%, impurities <0.5%).

appendix:

ASTM C633-13(2017)

Standard test method for adhesion or cohesive strength of thermal spray coatings

1. Scope

1.1 This standard specifies a test method for determining the adhesion or cohesive strength of thermal spray coatings by tensile testing. It is applicable to metallic, ceramic, and composite coatings.

Target customers

Including cemented carbide coatings (such as WC-Co, Cr_3C_2 - NiCr), used in flame spraying, arc spraying, plasma spraying (such as APS, VPS), HVOF, DGS and other processes.

Measurement target :

Adhesion: The bonding strength between the coating and the substrate, measured in MPa.

Cohesive strength: The bonding strength within the coating, measured in MPa.

1.2 This method is not applicable to ultra-thin coatings with a thickness of less than 0.1 mm.

1.3 This standard does not cover coating preparation processes, only test methods.

1.4 The values are expressed in metric units (MPa). The imperial units (psi) in parentheses are for reference only.

2. References

This standard references the following documents:

ASTM E4-16 : Standard Practice for Force Calibration of Tensile Testing Machines.

ASTM E6-15 : Terminology of Mechanical Testing.

ASTM E177-14 : Terminology for Precision and Bias in Engineering Data.

ASTM E691-16 : Comparison and evaluation of precision between test methods.

3. Terms and Definitions

Adhesion Strength : The tensile stress required for separation between the coating and the substrate interface, measured in MPa.

Cohesion Strength : The tensile stress required for separation of particles within the coating, measured in MPa.

Thermal spray coating : A coating deposited on the substrate surface by a thermal spray process (such as APS, HVOF).

Failure Mode :

Adhesion failure: Fracture at the interface between the coating and the substrate.

Cohesive failure: Fracture within the coating.

Mixed failure: A combination of adhesive and cohesive failure.

4. Significance and Use

This test method is used to evaluate the bond quality of thermal spray coatings and is suitable for quality control, material development, and performance verification.

Typical applications: aerospace (turbine blade coatings), industrial equipment (wear resistant coatings) and energy industry (drilling equipment coatings).

Example: WC-Co coating (HVOF) bond strength is typically 50-80 MPa, VPS coating can reach 60-90 MPa.

5. Test equipment

Tensile testing machine :

Meets ASTM E4 requirements, force calibration accuracy ±1%.

Loading speed: 0.015-0.025 mm/s (0.6-1.0 mm/min).

Fixture :

Cylindrical fixture, 25.4 mm (1.0 in) diameter, with alignment error <0.05 mm at both ends.

Clamp material: high strength steel, hardness ≥HRC 40.

Adhesive :

High-strength epoxy resin (such as FM 1000), strength ≥70 MPa.

Curing conditions: as recommended by the manufacturer (e.g. 150°C, 2 hours).

6. Sample preparation

Sample size :

Cylindrical specimens, 25.4 mm (1.0 in) diameter, substrate thickness ≥ 5 mm.

Coating thickness: 0.1-1.0 mm (depending on the process).

Substrate :

Material: Usually steel, stainless steel or aluminum, surface roughened by sandblasting (Ra 3-5 μm).

Coating preparation :

Spraying using actual production processes (e.g. HVOF, APS).

The coating surface needs to be flat, with a roughness of Ra 5-15 μm .

Bonding :

Bond the coated specimen to another cylindrical fixture of the same size.

Adhesive thickness: 0.05-0.2 mm, apply evenly and avoid bubbles.

Quantity : At least 5 specimens per group, representative test.

7. Experimental Procedure

Calibration : Testing machine force calibration , accuracy ±1%.

Installation : Clamp the specimen in the testing machine fixture, ensuring an alignment error of <0.05 mm.

Loading : Apply tensile load at a speed of 0.015-0.025 mm/s until the specimen fails.

Record :

Maximum tensile force, in N (or lb).

Failure mode (adhesive, cohesive or mixed).

calculate :

Bond strength (MPa) = maximum tensile force (N) / sample cross-sectional area (mm^2) .

Cross-sectional area: 502.7 mm² (diameter 25.4 mm).

8. Test conditions

Environment : temperature 23±2°C, humidity 50±10%, no vibration and corrosive gas.

Equipment : The testing machine should be protected from overheating or overloading.

9. Reporting of results

Report Contents :

Coating material and substrate information (e.g. WC-12Co, steel substrate).

Coating thickness (μm) and preparation process (HVOF, APS, etc.).

Adhesive type and curing conditions.

Mean values of bond strength (MPa), including standard deviation.

Failure mode (adhesive, cohesive or mixed), with photographs.

Test date, operator and equipment number.

Example : WC-Co coating (HVOF), bonding strength 65±5 MPa, failure mode is mixed failure.

10. Precision and Bias

Precision :

Intra-laboratory repeatability: standard deviation <5%.

Inter-laboratory reproducibility: standard deviation <10%.

deviation :

Possible sources: specimen alignment errors, insufficient adhesive strength, coating defects.

Control measures: Strictly follow the test procedures and check the quality of samples.

11. Appendix (reference)

Appendix X1 : Adhesive Selection Guide.

Recommended: FM 1000 epoxy resin, strength ≥ 70 MPa.

Appendix X2 : Failure Mode Analysis Example.

Examples: Adhesive failure (interfacial debonding), cohesive failure (fracture within the coating).

12. Keywords

Thermal spray coatings, adhesion, cohesive strength, tensile testing, bond strength.

appendix:

ASTM E2109-01(2014)
Standard test method for percent apparent porosity of thermal spray coatings

1. Scope

1.1 This standard specifies a test method for determining the percent apparent porosity of thermal spray coatings by microscopic analysis. It is applicable to metallic, ceramic, and composite coatings.
Applicable objects : including cemented carbide coatings (such as WC-Co, Cr_3C_2 - NiCr), used in plasma spraying (APS, VPS), HVOF, DGS and other processes.
Measurement target :
Apparent porosity: The percentage of pore area in the coating cross section to the total area, expressed in %.

1.2 This method is applicable to coatings with a thickness of ≥ 0.05 mm.

1.3 This standard does not address the causes of porosity or the coating preparation process, only the test method.

1.4 The values are expressed in metric units (%). The imperial units in parentheses are for reference only.

2. References

This standard references the following documents:
ASTM E3-11 : Standard Practice for Preparation of Microstructure Specimens of Metallic Materials.
ASTM E7-17 : Terminology for Microstructural Analysis of Metallic Materials.
ASTM E1245-03(2016) : Standard practice for determining the amount of inclusions or second phases in materials by image analysis.
ASTM E177-14 : Terminology for Precision and Bias in Engineering Data.

3. Terms and Definitions

Apparent Porosity : The percentage of pore area in the coating cross section to the total area, measured by microscopic image analysis, in %.
Thermal spray coating : A coating deposited on the substrate surface by a thermal spray process (such as APS, HVOF).
Porosity : Tiny voids within a coating or at an interface that may be caused by unmelted particles, gas entrapment, or shrinkage on cooling.
Field of View : The area observed by a microscope, usually rectangular or circular.

4. Significance and Use

This test method is used to evaluate the porosity of thermal spray coatings, which affects the corrosion resistance, wear resistance and bond strength of the coating.

Typical applications:

Aerospace (turbine blade coatings): porosity < 1% (VPS).

Industrial equipment (wear-resistant coating): porosity < 2% (HVOF).

Energy industry (drilling equipment coating): porosity <5% (APS).

Example: WC-Co coating (HVOF) porosity is typically 0.5-2%, while VPS coating can be <1%.

5. Test equipment

Optical Microscope :

Magnification: 100-1000 times, 200-500 times recommended.

Resolution: Can distinguish pore size ≥1 μm .

Scanning Electron Microscope (SEM) (optional):

Used for high-precision analysis, with a magnification of 500-2000 times.

Image analysis software :

It complies with ASTM E1245 requirements and can automatically identify and calculate pore area.

Cutting equipment :

Precision cutting machine to ensure smooth cross section.

Grinding and polishing equipment :

Sandpaper (240-1200 grit) and polishing cloth, using aluminum oxide or diamond suspension.

6. Sample preparation

Sample size :

Cross-sectional dimensions: at least 10 mm × 10 mm, coating thickness ≥ 0.05 mm.

Cutting :

Use a low speed precision cutter and coolant (such as water) to prevent overheating.

mosaic :

The specimens were mounted in epoxy resin to ensure a stable cross section.

Grinding and polishing :

Grinding: Use sandpaper No. 240, 400, 800, 1200 to gradually reduce scratches.

Polishing: Use 1 μm diamond suspension and polishing cloth speed 150-200 rpm.

Surface requirements: no scratches, pores are clearly visible.

clean :

Wash with ethanol, ultrasonically clean for 5 minutes, and dry.

Quantity : At least 3 specimens per group, representative test.

7. Experimental Procedure

Calibration : Microscope magnification calibration, accuracy ±2%.

Field of view selection :

5-10 fields of view were randomly selected to cover different areas of the coating cross section.

Area of each field of view: at least 0.01 mm² (200x magnification).

Image acquisition :

Take images using an optical microscope or SEM to ensure high pore contrast.

The pores appear dark and the coating matrix appears light.

Image analysis :

Porosity was identified using image analysis software (compliant with ASTM E1245).

Set threshold: exclude noise based on pore gray value.

calculate :

Apparent porosity (%) = (total pore area/total field of view) × 100.

The mean and standard deviation were calculated for 5-10 fields.

8. Test conditions

Environment : Temperature 23±2°C, humidity 50±10%, no vibration and dust.

Illumination : Use brightfield or darkfield illumination on the microscope to ensure that the pores are clear.

Equipment : Microscope lens clean to avoid artifacts.

9. Reporting of results

Report Contents :

Coating material and substrate information (e.g. WC-12Co, steel substrate).

Coating thickness and preparation process (HVOF, APS, etc.).

Microscope magnification and number of fields of view.

Average apparent porosity (%) including standard deviation.

Description of pore distribution (homogeneity, size range), with image.

Test date, operator and equipment number.

Example : WC-Co coating (HVOF), porosity 1.2±0.3%, uniform pore distribution, maximum pore size <5 μm .

10. Precision and Bias

Precision :

Intra-laboratory repeatability: standard deviation <0.5%.

Inter-laboratory reproducibility: standard deviation <1.0%.

deviation :

Possible sources: insufficient specimen polishing, improper image threshold setting, and biased field of view selection.

Control measures: Strictly follow the sample preparation and analysis procedures and increase the number of fields of view.

11. Appendix (reference)

Appendix X1 : Microscope Magnification Selection Guide.

Recommended: coating thickness 0.1-0.5 mm, use 200-500 times.

Appendix X2 : Image Analysis Software Setup Recommendations.

Example: Grayscale threshold setting range (0-255), pore identification threshold <50.

12. Keywords

Thermal spray coatings, surface porosity, microscopic analysis, image analysis, pore distribution.

appendix:

EN 657:2005

Thermal Spraying - Terminology and Classification

1. Scope

1.1 This European Standard defines the terms and classifications related to thermal spraying technology and is applicable to various thermal spraying processes (e.g. flame spraying, arc spraying, plasma spraying, etc.).

Applicable objects : including but not limited to metal coatings (such as zinc, aluminum), ceramic coatings (such as alumina, zirconium oxide) and composite coatings (such as WC-Co cemented carbide).

Purpose : To provide unified terminology to facilitate technical communication, standard setting and product description.

1.2 This standard does not address specific process parameters or performance requirements and is limited to terminology and classification.

2. Normative references

This standard refers to the following documents, and their clauses become clauses of this standard through reference in this standard.

EN 13507:2018 - Thermal spraying — Surface preparation of metal parts.

EN 13204:2017 - Thermal spraying — Powders — Compositions, technical delivery conditions.

ISO 14918:1998 - Thermal spraying — Inspection and acceptance testing documentation.

Note : If there is a revision, the latest version applies.

3. Terms and Definitions

This standard defines the following thermal spray-related terms, organized by process classification and technical characteristics:

3.1 Thermal spraying process

Thermal Spraying :

A coating process is formed by heating the material to a molten or semi-molten state and spraying it onto the surface of the substrate at high speed.

Flame Spraying :

A process that uses fuel gas (such as acetylene, propane) to burn with oxygen to produce a flame flow to melt and spray the material.

Arc Spraying :

A process in which an electric arc is generated between two conductive wires to heat the material and compressed air is used to eject molten particles.

Plasma Spraying :

A process that uses a plasma arc (temperature 10,000-15,000°C) to melt and spray the material, including atmospheric plasma spraying (APS) and vacuum plasma spraying (VPS).

High-Velocity Oxy-Fuel Spraying (HVOF) :

A process in which a supersonic flame (500-1000 m/s) is produced by burning fuel (such as kerosene) with oxygen.

High Explosive Spraying (DGS, Detonation Gun Spraying) :

A process in which a high-pressure shock wave is produced by a controlled explosion (oxygen mixed with acetylene) to spray.

3.2 Materials and coatings

Spray Material :

Powders, wires, rods or ropes for thermal spraying of materials such as metals, alloys, ceramics or composites.

Coating :

The layered structure formed on the substrate surface during thermal spraying.

Bond Coat :

the coating and the substrate that enhances adhesion, usually a metal (such as Ni-Cr, Ni-Al).

Cermet Coating :

A composite coating composed of carbides (such as WC, Cr_3C_2) and metal bonding phases (such as Co, Ni).

Splat :

The flat structure formed by the rapid cooling of molten or semi-molten particles after impacting the substrate is the basic unit of the coating.

3.3 Process parameters and performance

Spray Distance :

The distance from the spray gun nozzle to the substrate surface is in mm, usually 100-200 mm.

Feed Rate :

The amount of powder supplied per unit time, in g/min.

Bond Strength :

The adhesion between the coating and the substrate or within the coating, measured in MPa.

Porosity :

The percentage of pore volume in the coating to the total volume, expressed in %, affects corrosion resistance and wear resistance.

Surface **Roughness**

The microscopic roughness of the coating surface is usually expressed as Ra (arithmetic mean roughness) in µm .

3.4 Defects and Failures

Crack :

Cracks within a coating or at an interface may be caused by thermal or mechanical stress.

Delamination :

The phenomenon of coating peeling away from the substrate or internal layers.

Oxide Inclusion :

Oxide particles formed in the coating due to oxidation reaction.

4. Classification

4.1 Classification by process

Gas Thermal Spraying :

Including flame spraying, arc spraying and HVOF.

Plasma Thermal Spraying :

Including APS and VPS.

Explosive Thermal Spraying :

Including DGS.

4.2 Classification by material

Metallic Coatings :

Such as zinc, aluminum and nickel based alloys.

Ceramic Coatings :

Such as Al_2O_3, ZrO_2.

Composite Coatings :

Such as WC - Co, Cr_3C_2 - NiCr .

4.3 Classification by Application

Protective Coatings :

Used for corrosion resistance, wear resistance or high temperature resistance, such as industrial pipeline coating.

Functional Coatings :

Used for specific functions such as conductive or insulating coatings.

Repair Coatings :

Used to repair worn or corroded parts, such as mold repair.

5. Appendix (reference)

Appendix A : Schematic diagram of the thermal spray process.

Example: Schematic diagram of flame spraying, showing the flame flow, nozzle and substrate position.

Appendix B : Terminology comparison table for common coating materials.

Examples: WC-Co (hard alloy), NiCr (nickel-chromium alloy).

6. Applicability and Limitations

Applicability : Technical documentation, standards development and training for the thermal spray industry.

limit :

It does not include specific process parameters or performance test methods, and reference to other

standards (such as EN 13507, ISO 14923) is required.
Not suitable for non-thermal spraying processes such as cold spraying.

appendix:

EN 13507:2018

Thermal spraying - surface preparation of metal parts and components

1. Scope

1.1 This European Standard specifies requirements, methods and acceptance criteria for the surface preparation of metallic parts and assemblies prior to thermal spraying.

Applicable objects : including but not limited to steel, stainless steel, aluminum alloy and titanium alloy parts, suitable for subsequent thermal spray coatings (such as WC-Co, Cr_3C_2 - NiCr).

Purpose : To ensure surface cleanliness and roughness and enhance the adhesion of the coating to the substrate.

1.2 This standard applies to flame spraying, arc spraying, plasma spraying (APS, VPS), HVOF and DGS processes.

1.3 This standard does not cover the pretreatment of non-metallic substrates or coating preparation processes.

2. Normative references

This standard refers to the following documents, and their clauses become clauses of this standard through reference in this standard.

EN 657:2005 - Thermal spraying — Terminology and classification.

EN 1011-1:2009 - Welding — Fusion welding of steels — Part 1: General guidance on materials and procedures.

EN ISO 8501-1:2007 - Surface preparation of steel — Visual assessment of rust levels and preparation grades — Part 1: Rust levels and preparation grades.

EN ISO 2063:2005 - Thermal spraying — Metallic and inorganic coatings — Zinc, aluminium and their alloys.

Note : If there is a revision, the latest version applies.

3. Terms and Definitions

This standard uses the following terms and definitions, referring to EN 657:2005:

Surface Preparation : The process of removing surface contamination and enhancing coating adhesion by cleaning, roughening or treating.

Roughness : The microscopic unevenness of the surface, usually expressed as Ra (arithmetic mean roughness), with the unit of μm .

Blasting : A process that uses high-pressure air or wheel-type spraying of hard particles (such as sand and steel shot) to roughen the surface.

Cleanliness : The degree to which a surface is free of oil, rust and oxides, usually rated according to EN ISO 8501-1.

4. Requirements

4.1 Surface cleanliness

Objective : Remove grease, rust, mill scale, weld slag and contaminants.

Rating :

Steel: EN ISO 8501-1 Sa 2 ½ (near white), free from visible oil and rust.

Aluminium alloys: EN ISO 8501-1 Sa 2 (thoroughly rust-free), free of loose particles.

Inspection method : visual inspection or magnifying glass (magnification 5-10 times).

4.2 Surface roughness

scope :

Recommended Ra 3-5 μm (natural roughness after sandblasting).

μm (to be agreed) depending on coating type .

Measurement method : Use a stylus surface profiler (refer to EN ISO 4287) with a sampling length of 2.5 mm.

Tolerance : Ra deviation ±1 μm .

4.3 Residual stress control

Requirements : After pretreatment, the surface residual stress should be minimized to avoid cracks.

Method : Control the sandblasting pressure (0.2-0.7 MPa) and angle (45-90°).

4.4 Substrate Integrity

Requirements : Pretreatment must not cause significant deformation or damage to the substrate (such as cracks, peeling).

Inspection : Visual inspection or non-destructive testing (such as magnetic particle inspection).

5. Preprocessing methods

5.1 Cleaning

Degreasing :

Method: Cleaning with organic solvents (such as trichloroethylene, ethanol) or ultrasonic cleaning.

Time: 5-10 minutes, make sure there is no oil stain.

Rust Removal :

Method: pickling (such as 10% hydrochloric acid solution) or mechanical cleaning (such as wire brush).

Note: Neutralize and rinse after pickling.

5.2 Sandblasting

equipment :

Sand blasting machine, pressure 0.2-0.7 MPa, nozzle diameter 6-10 mm.

Abrasive :

Steel shot: diameter 0.3-1.0 mm, hardness ≥HRC 40.

Sand: Quartz sand or corundum, particle size 0.2-0.8 mm.

Purity: Impurities <1%.

parameter :

Spray distance: 100-150 mm.

Spray angle: 45-90° (adjusted according to the shape of the substrate).

Sandblasting time: until the specified roughness and cleanliness are achieved.

Safety : Operators should wear protective equipment to avoid inhaling dust.

5.3 Other methods

Mechanical roughening :

Use grinding wheel or grinder, suitable for local area, roughness Ra 3-5 μm .

Heat Treatment :

Preheat the substrate to 50-150°C to enhance adhesion and avoid condensation.

6. Inspection and Acceptance

Inspection method :

Cleanliness : Visual rating to EN ISO 8501-1.

Roughness : measured by stylus profilometer, and the average value was taken from 5 points.

Surface integrity : visual or non-destructive testing.

Acceptance criteria :

Cleanliness level Sa 2 ½ (steel) or Sa 2 (aluminium).

The roughness is within the specified range (Ra 3-5 μm).

No obvious damage or contamination.

Records : pretreatment process parameters, inspection results and dates.

7. Test conditions

Environment : Temperature 15-30°C, humidity <70%, no dust and corrosive gas.

Equipment : Sandblasting machines and measuring tools need to be calibrated regularly (accuracy ±5%).

8. Reporting of results

Report Contents :

Substrate material and part information (steel, stainless steel, etc.).

Pretreatment methods (sandblasting, degreasing, etc.).

Process parameters (pressure, distance, abrasive type).

Cleanliness rating and roughness measurement (Ra).

Surface integrity inspection results.

Test date, operator and equipment number.

Example : Steel substrate, sandblasting (steel shot 0.5 mm, 0.5 MPa, 150 mm), Ra 4.2 μm , cleanliness Sa 2 ½ .

9. Applicability and Limitations

Applicability : Suitable for metal parts and components before thermal spraying to enhance coating adhesion.

limit :

Not suitable for non-metallic substrates (e.g. ceramics, polymers).

The performance of subsequent coatings is not specified and reference is made to EN 657 or ISO 14923.

10. Appendix (reference)

Appendix A : Recommended sandblasting parameters table.

Example: Steel substrate, pressure 0.5 MPa, distance 120 mm, steel shot 0.5 mm, Ra 4-6 μm .

Appendix B : Cleanliness Rating Example Photos (Sa 2 ½ Standard).

Appendix: .

GB/T 18719-2002
Thermal spray powder

1. Scope

1.1 This standard specifies the classification, technical requirements, test methods, and inspection rules for powders used in thermal spraying processes.

Applicable objects : including metal powders (such as zinc, aluminum), ceramic powders (such as alumina, zirconium oxide) and composite powders (such as WC-Co cemented carbide).

Purpose : To ensure that the chemical composition, particle size distribution and morphology of the powder meet the requirements of the thermal spraying process.

1.2 This standard applies to processes such as flame spraying, arc spraying, plasma spraying (APS, VPS), HVOF and DGS.

1.3 This standard does not address the powder preparation process or coating properties, but focuses only on the powder itself.

2. Normative references

This standard refers to the following documents, and their clauses become clauses of this standard through reference in this standard.

GB/T 5314-2002 - Rockwell hardness test method for metallic materials.

GB/T 13320-1991 - Terminology of powder metallurgy.

GB/T 1479.1-1993 - Metal powder particle size determination method - Sieving method.

GB/T 1482-2010 - Sampling methods and chemical analysis methods for metal powders.

Note : If there is a revision, the latest version applies.

3. Terms and Definitions

This standard adopts the following terms and definitions, with reference to GB/T 13320-1991:

Thermal Spray Powder : Granular material used in thermal spraying process, which can be metal, alloy, ceramic or composite material.

Particle Size : The maximum linear size of powder particles, in µm .

Particle Size Distribution : The percentage distribution of powder particles according to the size range.

Flowability : The flow characteristics of powder during the powder feeding process , the unit is s/50g.

Apparent Density : The mass of a powder per unit volume, expressed in g/ cm^3 .

4. Classification

4.1 Classification by material type

Metal powder :

Such as zinc (Zn), aluminum (Al), nickel (Ni), and copper (Cu).

Ceramic powder :

aluminum oxide (Al_2O_3) and zirconium oxide (ZrO_2) .

Composite powder :

Such as WC-Co (tungsten cobalt cemented carbide), Cr_3C_2 - NiCr (chromium carbide nickel chromium).

4.2 Classification by morphology

Spherical powder : The particles are approximately spherical and have good fluidity.

Irregular powder : Irregular particle shape, suitable for specific processes.

Hollow powder : particles with voids inside to reduce density.

5. Technical requirements

5.1 Chemical composition

Require :

The content deviation of main elements is ±0.5% (such as WC, Co).

Total impurity content <1% (oxygen <0.5%, sulfur <0.1%).

Test method : Chemical analysis method or spectral analysis method specified in GB/T 1482.

5.2 Particle size distribution

scope :

Common range: 10-75 μm .

Specific process:

APS/VPS: 10-50 μm .

HVOF: 10-45 μm .

DGS: 10-50 μm .

tolerance :

90% of the particles are within the specified range.

<5% of particles exceed the upper particle size limit.

Test method : GB/T 1479.1 screening method or laser particle size analysis method.

5.3 Liquidity

Require :

Spherical powder: ≤20 s/50g.

Irregular powder: ≤30 s/50g.

Test method : Use Hall Flowmeter and measure according to the Appendix of GB/T 1479.1.

5.4 Apparent density

Require :

Spherical powder: 2.0-5.0 g/cm³ (depending on the material).

Irregular powder: 1.5-4.0 g/ cm³ .

Test method : Apparent density determination method specified in GB/T 1479.1.

5.5 Microstructure

Require :

There is no serious oxidation or contamination on the particle surface.

The hollow powder wall thickness is uniform and there is no cracking.

Inspection method : optical microscopy (magnification 100-500 times) or scanning electron microscopy (SEM).

6. Test methods

6.1 Sampling

Method : Stratified sampling or mechanical sampling as specified in GB/T 1482.

Quantity : The sampling volume of each batch is ≥200 g, representative samples.

6.2 Chemical composition analysis

Method : Spectroscopic analysis or chemical titration method specified in GB/T 1482.

Accuracy : Main element error ±0.2%, impurity error ±0.05%.

6.3 Particle size determination

Method : GB/T 1479.1 sieving method (standard sieves: 45, 63, 75 μm) or laser particle size analyzer.

Repeatability : 3 measurements, deviation <5%.

6.4 Fluidity determination

Method : GB/T 1479.1 Hall flow cup method , record the time for 50 g powder to pass through.

Repeatability : 3 measurements, average value.

6.5 Apparent density determination

Method : GB/T 1479.1 standard measuring cup method, measuring the mass of 100 cm^3 powder .

Repeatability : Deviation <0.1 g/ cm^3 after 3 measurements .

6.6 Microstructural examination

Method : Optical microscope or SEM, magnification 100-500 times.

Report : Particle morphology, surface condition and hollow noodle wall thickness.

7. Inspection Rules

Batch definition : The same production batch, weight ≤ 500 kg.

Sampling : 1-3 samples are taken from each batch, adjusted according to the batch size.

Acceptance criteria :

The chemical composition, particle size distribution, fluidity and apparent density shall comply with the requirements of Sections 5.1-5.4.

There are no obvious defects in the microstructure.

Unqualified treatment : Unqualified samples need to be retested or scrapped.

8. Marking, packaging and transportation

mark :

The material name (such as WC-12Co), batch number and production date are marked on the package.

Package :

Use sealed plastic bags or metal cans to prevent moisture and oxidation.

Weight per package: 5-25 kg.

Transport : Avoid high temperature (<40°C) and humidity to prevent powder contamination.

9. Reporting of results

Report Contents :

Powder material and classification information.

Chemical composition analysis results.

Particle size distribution, flowability, apparent density measurements.

Results of microstructural examination (photos attached).

Test method and equipment number.

Production batch number, date and inspector's signature.

Example : WC-12Co powder, particle size 10-45 μm , flowability 18 s/50g, apparent density 4.2 g/cm³ , no surface oxidation.

10. Applicability and Limitations

Applicability : Suitable for the production, inspection and use of thermal spray powders.

limit :

Not suitable for use with wire, rod or rope.

There are no regulations on coating performance, please refer to GB/T 8642 or ISO 14923.

11. Appendix (reference)

Appendix A : Recommended particle size distribution table.

Example: APS powder, 10-50 μm , >90% compliance.

Appendix B : Schematic diagram of the fluidity test device.

appendix:

GB/T 17391-2008

Thermal spray coating adhesion test method

1. Scope

1.1 This standard specifies test methods for determining the adhesion of thermal spray coatings and is applicable to metal, ceramic, and composite coatings.

Applicable objects : including cemented carbide coatings (such as WC-Co, Cr_3C_2 - NiCr), used in flame spraying, arc spraying, plasma spraying (APS, VPS), HVOF and DGS processes.

Measurement target :

Adhesion: The bonding strength between the coating and the substrate, measured in MPa.

Cohesive strength: The bonding strength within the coating, measured in MPa.

1.2 This method is applicable to coatings with a thickness of ≥ 0.1 mm.

1.3 This standard does not involve coating preparation processes, but only provides adhesion test methods.

2. Normative references

This standard refers to the following documents, and their clauses become clauses of this standard through reference in this standard.

GB/T 531-1999 - Test method for Vickers hardness of metallic materials.

GB/T 13320-1991 - Terminology of powder metallurgy.

GB/T 14623-2003 - Tensile test methods for metallic materials.

GB/T 8642-2002 - Determination of thickness of thermally sprayed zinc, aluminium and their alloy coatings.

Note : If there is a revision, the latest version applies.

3. Terms and Definitions

This standard adopts the following terms and definitions, with reference to GB/T 13320-1991:

Adhesion Strength : The tensile stress required for separation between the coating and the substrate interface, measured in MPa.

Cohesion Strength : The tensile stress required for separation of particles within the coating, measured in MPa.

Thermal Spray Coating : A coating deposited on the surface of the substrate through a thermal spraying process.

Failure Mode :

Adhesion failure: Fracture at the interface between the coating and the substrate.

Cohesive failure: Fracture within the coating.

Mixed failure: A combination of adhesive and cohesive failure.

4. Significance and Use

This test method is used to evaluate the bond quality of thermal spray coatings and is suitable for quality control, material development, and performance verification.

Typical applications:

Aerospace (turbine blade coating): WC-Co coating adhesion 50-80 MPa.

Industrial equipment (wear-resistant coating): HVOF coating adhesion 60-90 MPa.

Energy industry (drilling equipment coating): Cr_3C_2 - NiCr coating adhesion 40-70 MPa.

5. Test equipment

Tensile testing machine :

Meets the requirements of GB/T 14623, force calibration accuracy ±1%.

Loading speed: 0.5-2 mm/min.

Fixture :

Cylindrical fixture, 25 mm diameter, alignment error <0.05 mm at both ends.

Material: high strength steel, hardness ≥HRC 40.

Adhesive :

High-strength epoxy resin (such as FM 1000), tensile strength ≥ 70 MPa.

Curing conditions: as recommended by the manufacturer (e.g. 120°C, 1-2 hours).

6. Sample preparation

Sample size :

Cylindrical specimen, diameter 25 mm, substrate thickness ≥ 5 mm.

Coating thickness: 0.1-1.0 mm (depending on the process).

Substrate :

Material: Usually steel, stainless steel or aluminum, surface roughened by sandblasting (Ra 3-5 μm).

Coating preparation :

Spraying using actual production processes (e.g. HVOF, APS).

The coating surface needs to be flat, with a roughness of Ra 5-15 μm .

Bonding :

Bond the coated specimen to another cylindrical fixture of the same size.

Adhesive thickness: 0.05-0.2 mm, apply evenly and avoid bubbles.

Quantity : At least 5 specimens per group, representative test.

7. Experimental Procedure

Calibration : Testing machine force calibration , accuracy ±1%.

Installation : Clamp the specimen in the testing machine fixture, ensuring an alignment error of <0.05 mm.

Loading : Apply tensile load at a rate of 0.5-2 mm/min until the specimen fails.

Record :

Maximum tensile force, unit: N.

Failure mode (adhesive, cohesive or mixed).

calculate :

Adhesion or cohesive strength (MPa) = maximum tensile force (N) / sample cross-sectional area (mm²) .

Cross-sectional area: 490.9 mm² (diameter 25 mm).

8. Test conditions

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

Equipment : The testing machine should be protected from overheating or overloading.

9. Reporting of results

Report Contents :

Coating material and substrate information (e.g. WC-12Co, steel substrate).

Coating thickness (μm) and preparation process (HVOF, APS, etc.).

Adhesive type and curing conditions.

Mean values of adhesion or cohesion strength (MPa) including standard deviation.

Failure mode (adhesive, cohesive or mixed), with photographs.

Test date, operator and equipment number.

Example : WC-Co coating (HVOF), adhesion 65 ± 5 MPa, failure mode is mixed failure.

10. Precision and Bias

Precision :

Intra-laboratory repeatability: standard deviation <5%.

Inter-laboratory reproducibility: standard deviation <10%.

deviation :

Possible sources: specimen alignment errors, insufficient adhesive strength, coating defects.

Control measures: Strictly follow the test procedures and check the quality of samples.

11. Appendix (reference)

Appendix A : Adhesive Selection Guide.

Recommended: FM 1000 epoxy resin, strength ≥ 70 MPa.

Appendix B : Failure Mode Analysis Examples.

Examples: Adhesive failure (interfacial debonding), cohesive failure (fracture within the coating).

12. Applicability and Limitations

Applicability : Suitable for adhesion and cohesive strength testing of thermal spray coatings.

limit :

Not suitable for ultra-thin coatings with a thickness of < 0.1 mm.

There are no regulations on coating porosity or wear resistance, please refer to GB/T 8642 or ASTM G65.

appendix:

AMS 2437: HVOF Process Specification

AMS 2437 is not a HVOF (High Velocity Oxygen Fuel Spray) process specification, but a specification for the Plasma Spray Deposition process. The following is a detailed description of AMS 2437, as well as a comparison and clarification with the HVOF process specification.

AMS 2437: Plasma Spray Process Specification

AMS 2437 is a standard published by SAE International. The latest version is AMS 2437D (2019-12-13), titled "Coating, Plasma Spray Deposition". This standard specifies the engineering requirements and coating performance for depositing coatings on parts by plasma spraying.

1. Scope

Applicable objects : Suitable for metal, ceramic and composite material coatings (such as WC-Co, alumina), used in aerospace, industry and other fields.

Process : Plasma spraying (APS), where a high temperature plasma arc (10,000-15,000°C) melts the powder and sprays it onto the substrate surface.

Purpose : To provide wear resistant, corrosion resistant or thermal barrier coatings (e.g. TBC) for high wear applications.

Thickness : Typically <1 mm, depending on application .

2. Key requirements

Coating properties :

Adhesion: Assessed by Cup Test or Bend Test, in accordance with Section 3.6.1.

Hardness: According to Section 3.6.5, depending on the coating material (e.g. WC-Co hardness ≥ 1000 HV).

Porosity: Typically <5%, by microscopic examination.

test :

Acceptance test (4.2.1): Each batch is tested for adhesion and hardness.

Periodic testing (4.2.2): Regular verification of process stability.

Pre-production testing (4.2.3): New processes or materials require additional verification.

3. Restrictions

Not suitable for HVOF process.

No double coating (i.e. spraying over an existing coat) is involved.

HVOF process specification: AMS 2447

Users may mistakenly confuse AMS 2437 with the HVOF process specification. The correct specification for the HVOF process is AMS 2447, the latest version of which is AMS 2447D (2019-01-14), titled "Coating, Thermal Spray, High Velocity Oxygen/Fuel Process".

1. Scope

Applicable objects : Suitable for coatings deposited by HVOF process, such as cemented carbide

(WC-Co, WC-CoCr), metal alloy (NiCr), widely used in aerospace high wear resistant applications.

Process : HVOF produces a supersonic flame (500-1000 m/s) by burning fuel (such as kerosene) with oxygen to deposit a high- density coating.

Purpose : To provide excellent wear and corrosion resistance, better than plasma spraying (such as AMS 2437).

2. Key requirements

Coating properties :

Porosity: <2%, significantly lower than plasma spraying.

Adhesion: Typically >70 MPa (vs. 50-60 MPa for plasma spraying).

Surface roughness: Ra 6-16 µm (depending on the application, such as seals need <0.15 µm).

Material :

Commonly used powders: WC-17Co, WC-10Co-4Cr (AMS 7881, AMS 7882).

Thickness range: 25-500 µm (carbide), alloy coatings can be thicker.

test :

Fluorescent Penetrant Inspection (FPI): Checks for cracks.

Barkhausen noise detection: Evaluating grinding burn.

Restrictions : Not suitable for double coating.

3. Typical applications

Aerospace: turbine blades, landing gear (adhesion 60-90 MPa).

Industry: wear-resistant rollers, seals.

4. Comparison with AMS 2437

Process : AMS 2437 (plasma spray) has high temperature and high porosity (3-5%); AMS 2447 (HVOF) has high speed and low porosity (<2%).

Performance : HVOF coatings (such as WC-Co) have better adhesion and wear resistance than plasma spraying.

Application : AMS 2437 is more suitable for thermal barrier coatings (such as ZrO_2), while AMS 2447 is more suitable for high wear resistant coatings (such as WC-Co).

appendix:

ISO 3252:2019
Powder Metallurgy Terminology
Powder metallurgy — Vocabulary

1. Scope

1.1 This International Standard defines terminology in the field of powder metallurgy, covering powder preparation, characterization, and application techniques.

Applicable objects : including metal powders (such as zinc, aluminum), ceramic powders (such as alumina) and composite powders (such as WC-Co cemented carbide), suitable for processes such as thermal spraying, sintering and additive manufacturing .

Purpose : To provide unified terminology to facilitate technical communication, standard setting and research.

1.2 This standard does not address specific process parameters or performance test methods but focuses only on term definitions.

2. Normative References

There are no direct references to other standards, but the terminology is related to ISO 4490 (determination of powder particle size) and ISO 3953 (extended terminology for powder metallurgy).

3. Terms and Definitions

This standard classifies various aspects of powder metallurgy and defines the following key terms:

3.1 Powder Characteristics

Powder : A loose material consisting of particles, with particle sizes usually ranging from 1 nm to 1 mm.

Particle Size : The maximum linear size of a single particle, expressed in μm or nm.

Particle Size Distribution : The percentage distribution of powder particles according to the size range, usually expressed as D10, D50, and D90.

Morphology : The shape and surface characteristics of particles, such as spherical, irregular, or polyhedral.

Specific Surface Area : The total surface area per unit mass of powder, expressed in m^2 / g.

3.2 Physical Properties

Apparent Density : The mass per unit volume of powder when no external force is applied, expressed in g/ cm^3 .

Tap Density : The mass per unit volume of powder after tapping , expressed in g/ cm^3 .

Flowability : The flow characteristics of powder under gravity or mechanical action, the unit is s/50g (Hall flow cup method).

Compressibility : The ability of a powder to reduce its volume after being compressed, expressed in g/ cm³ .

3.3 Chemical Properties

Chemical Composition : The percentage content of each element or compound in the powder.

Oxide Content : The mass fraction of oxide in powder, expressed in %.

Impurity : Unintended elements or compounds other than the main component.

3.4 Preparation and Processing

Atomization : The process of preparing powder by impinging molten metal with liquid or gas.

Mechanical Alloying : A process of mixing and alloying powder components through high-energy ball milling .

Sintering : The process of combining powder particles into porous or dense materials at high temperatures.

Thermal Spraying : A process in which powder is heated to a molten or semi-molten state and then sprayed onto the surface of the substrate.

3.5 Applications

Cermet : A composite material composed of carbide (such as WC) and a metal bonding phase (such as Co).

Additive Manufacturing : A process that uses layered deposition of powder to create parts, such as selective laser melting (SLM).

Coating : A protective or functional layer formed on the surface of a substrate by thermal spraying or deposition.

3.6 Test Methods

Sieving : A method for determining the particle size distribution of powders using a standard sieve.

Laser Diffraction Analysis : A technology that uses laser scattering to measure powder particle size distribution.

Microscopic Examination : Analyze powder morphology and defects using optical or scanning electron microscopy (SEM).

4. Classification

By material type :

Metal powder (such as Fe, Cu).

Ceramic powders (such as Al_2O_3 , ZrO_2) .

Composite powders (such as WC-Co).

By particle shape :

Spherical powder.

Irregular powder.

Porous or hollow powder.

By Application :

Structural materials.

Functional materials (such as conductive coatings).

5. Annexes

Appendix A : Glossary of terms (English-Chinese).

Examples: Particle Size, Flowability.

Appendix B : Schematic diagram of particle morphology.

Examples: spherical powder, needle-shaped powder.

6. Applicability and Limitations

Applicability : Technical documentation, standards development and training for the powder metallurgy industry, including the use of terminology for thermal spray powders.

limit :

It does not include specific test methods or process parameters, which require reference to standards such as ISO 4490.

Definitions of terms not applicable to fields other than powder metallurgy.

appendix:

ISO 14923:2003
Thermal spraying
—Characterization and testing of thermally sprayed coatings
Thermal Spraying
— Characterization and testing of thermal spray coatings

1. Scope

1.1 This International Standard specifies methods for characterizing and testing thermally sprayed coatings (TWCs) suitable for evaluating their properties and quality.
Applicable Objects: including metal coatings (such as zinc, nickel), ceramic coatings (such as alumina) and composite coatings (such as WC-Co cemented carbide/Cermet Coating), suitable for flame spraying (Flame Spraying / Flame Spraying), arc spraying (Arc Spraying / Arc Spraying), plasma spraying (Plasma Spraying, APS/VPS / Plasma Spraying, APS/VPS), HVOF and DGS processes.
Purpose: To provide standardized test methods to evaluate properties such as adhesion, porosity, and thickness.

1.2 This standard applies to coatings with a thickness (Thickness) ≥ 0.05 mm.

1.3 This standard does not cover the coating preparation process (Coating Preparation Process / Coating Preparation Process), only provides test methods and characterization techniques.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
ISO 4287:1997 - Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters / Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters
ISO 6507-1:2005 - Metallic materials — Vickers hardness test — Part 1: Test method
ISO 8501-1:2007 - Preparation of steel substrates before application of paints and related products — Visual assessment of surface cleanliness — Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings
ISO 9227:2017 - Corrosion tests in artificial atmospheres — Salt spray tests
Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions
This standard uses the following terms and definitions:
Thermally Sprayed Coating: A coating deposited on the surface of a substrate by a thermal spraying process.

Adhesion: The bonding strength between the coating and the substrate (Bonding Strength), measured in MPa.

Cohesion: The bonding strength between particles inside the coating, measured in MPa.

Porosity: The percentage of pore volume in a coating to the total volume, expressed in %.

Thickness: The vertical distance from the substrate surface to the top of the coating (Vertical Distance), in µm .

4. Characterization Methods

4.1 Thickness Measurement

Method:

Magnetic Method (ISO 2178): Applicable to non-magnetic coatings on magnetic substrates.

Eddy Current Method (ISO 2360): Applicable to non-conductive coatings on non-magnetic metal substrates.

Microscopic Method: Cross-Section observation, measure 5 points and take the average value.

Accuracy: ±5% or ±5 µm (whichever is greater).

4.2 Porosity Determination

Method:

Microscopic Method: Analysis of cross-sectional images to calculate the percentage of pore area.

Penetration Method: Use dye (Dye / Dye) or gas (Gas / Gas) penetration to assess pore connectivity.

Accuracy: ±1% or ±0.5% (depending on magnification).

4.3 Surface Roughness

Method: Stylus Profilometer (ISO 4287), measurement of Ra value.

Range: Typical value is 2-15 µm , depending on the application .

4.4 Microstructural Analysis

Method: Optical Microscope or Scanning Electron Microscope (SEM), Magnification 50-1000x.

Parameters: Observe Cracks, Oxide Inclusions and Splat Morphology.

5. Testing Methods

5.1 Adhesion Testing

Method : Tensile Test (ISO 4624) using an adhesive and a tensile testing machine.

Specimen: diameter 25 mm, coating thickness 0.1-1.0 mm.

Loading Rate: 0.5-2 mm/min.

Calculation: Adhesion (MPa) = Maximum Force / Cross -Sectional Area.

Failure Mode: Adhesive Failure or Cohesive Failure.

5.2 Hardness Testing

Method: Vickers Hardness Test (ISO 6507-1), Load 5-10 N.

Accuracy: ±5 HV or ±10% (whichever is greater).

5.3 Corrosion Resistance Testing

Method: Salt Spray Test (ISO 9227), Duration: 24-480 hours.

Evaluation: Record the Rust Area percentage.

5.4 Wear Resistance Testing

Method: Volume loss was measured according to ASTM G65 (Dry Sand / Rubber Wheel Test).

Accuracy: ±5% or ±0.1 mm³ .

6. Specimen Preparation

Dimensions:

Thickness Measurement: 10 mm × 10 mm × coating thickness.

Adhesion Testing: Diameter 25 mm, thickness ≥ 5 mm.

Surface Preparation: Sandblasting (Ra 3-5 μm), Contaminants removal.

Quantity: ≥3 specimens per group, representative testing.

7. Test Conditions

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

Equipment: Calibration (Calibration / Calibration), accuracy (Accuracy / Accuracy) ± 2%.

8. Test Report

Contents

Coating Material and Substrate information (e.g. WC-12Co, Steel Substrate).

Preparation process (Process / Preparation process, such as HVOF) and coating thickness (Thickness / Coating thickness).

Characterization Results (thickness, porosity, roughness).

Test Results (Test Results / Test Results, Adhesion, Hardness, Corrosion Resistance).

Failure Mode (Failure Mode) and Microstructure (Microstructure) photos.

Test date (Date / Test date), operator (Operator / Operator) and equipment number (Equipment Number / Equipment Number).

Example: WC-Co coating (HVOF), thickness 250 μm , porosity 1.5%, adhesion 70 MPa, failure mode is cohesive failure.

9. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <5%, Between Laboratories (Between Laboratories / Between Laboratories) <10%.

Bias: May be caused by uneven sample preparation or inadequate equipment calibration. Surface preparation quality needs to be controlled.

10. Annexes

Appendix A (Annex A / Appendix A): Thickness Measurement Diagram (Thickness Measurement Diagram / Thickness Measurement Diagram).
Appendix B (Annex B / Appendix B): Adhesion Test Specimen Preparation Procedure (Adhesion Test Specimen Preparation Procedure / Adhesion Test Specimen Preparation Procedure).

11. Applicability and Limitations

Applicability: Applicable to quality control and performance assessment of thermally sprayed coatings.
Limitations:
Not suitable for ultra-thin coatings with a thickness of < 0.05 mm.

The Coating Preparation Process is not specified and reference is made to ISO 14917:2017 - *Thermal spraying — Terminology, classification* .

appendix:

ISO 4505:2017
Metallic materials
— Hardness test — Test method
Metal Materials
— Hardness test — Test method

1. Scope

1.1 This International Standard specifies a general method for hardness testing of metallic materials. It is applicable to the Vickers Hardness, Brinell Hardness, and Rockwell Hardness tests.
Applicable Objects: Applicable to metal materials, including thermally sprayed coatings (such as WC-Co cemented carbide/Cermet Coating) and other metal parts.
Purpose: To provide a standardized hardness test method to ensure repeatability and comparability of results.

1.2 This standard applies to specimens with a thickness of ≥ 0.5 mm.

1.3 This standard does not cover hardness testing of nonmetallic materials such as ceramics or plastics but may be extended to metal matrix composites.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
ISO 6506-1:2014 - Metallic materials — Brinell hardness test — Part 1: Test method
ISO 6507-1:2018 - Metallic materials — Vickers hardness test — Part 1: Test method
ISO 6508-1:2016 - Metallic materials — Rockwell hardness test — Part 1: Test method
ISO 18265:2013 - Metallic materials — Conversion of hardness values
Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions:
Hardness: The ability of a material to resist local plastic deformation, usually measured by indentation.
Vickers Hardness (Vickers Hardness): The hardness measured by pressing a square cone-shaped diamond indenter (Diamond Indenter), expressed as HV.
Brinell Hardness (Brinell Hardness / Brinell Hardness): The hardness measured by indenting a carbide ball (Carbide Ball / Carbide Ball), expressed in HBW.
Rockwell Hardness: The hardness is measured by pressing a diamond or steel ball into the test piece and measuring the depth, expressed in HR (such as HRC, HRB).
Indentation : The permanent deformation mark left by the indenter on the surface of the specimen.

4. Principles of Test

Vickers Hardness: Use a 136° square cone diamond indenter to apply a specified load, measure the diagonal length of the indentation, and calculate the hardness value.
Brinell Hardness: Use a carbide ball to apply a load, measure the indentation diameter, and calculate the hardness value.
Rockwell Hardness: Apply a preload and main load, measure the indentation depth, and read the hardness value directly.

5. Test Methods

5.1 Vickers Hardness Test

Equipment: Vickers Hardness Tester, in accordance with ISO 6507-1.
Load: 0.01 kgf to 100 kgf (0.098 N to 980.7 N).
Procedure:
Apply the load and hold for 10-15 seconds.
Measure the diagonal length of the indentation at least twice and take the average value.
Calculation:
$HV = 1.8544 \times F / d^2$, where F is the load (N) and d is the average diagonal length (mm).
Accuracy: ±5 HV or ±5% (whichever is greater).

5.2 Brinell Hardness Test

Equipment: Brinell Hardness Tester, in accordance with ISO 6506-1.
Load: 1 kgf to 3000 kgf (9.807 N to 29420 N).
Ball Diameter: 1 mm, 2.5 mm, 5 mm or 10 mm.
Procedure:
Apply the load and hold for 10-15 seconds.
Measure the indentation diameter (Diameter) in at least two directions and take the average value.
Calculation:
$HBW = 0.102 \times (2F / (\pi D(D - \sqrt{(D^2 - d^2)})))$, where F is the load (N), D is the ball diameter (mm), and d is the indentation diameter (mm).
Accuracy: ±5 HBW or ±5% (whichever is greater).

5.3 Rockwell Hardness Test

Equipment: Rockwell Hardness Tester, in accordance with ISO 6508-1.
Load:
Preload: 10 kgf (98.07 N).
Main Load : 60 kgf , 100 kgf or 150 kgf (588.4 N, 980.7 N or 1471 N).
Indenter: Diamond Cone or Steel Ball.
Procedure:
Apply preload and hold for 2-5 seconds.
Apply the primary load and hold for 4-6 seconds.
Remove the main load and read the hardness value.

Accuracy: ±0.5 HRC or ±1% (whichever is greater).

6. Specimen Preparation

Surface Preparation: The surface of the sample must be flat, with a roughness of Ra < 0.8 μm , and the oxide scale and oil stains must be removed.

Thickness: Sample thickness ≥ 10 times of indentation depth.

Quantity: ≥3 specimens per group, representative testing.

7. Test Conditions

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

Equipment Calibration: Hardness tester accuracy ±2%, calibrated once a year.

8. Test Report

Contents

Specimen Material and Substrate information (e.g. WC-Co coating, Steel Substrate).

Test Method (Test Method / Test Method, such as Vickers Hardness).

Load (Load) and indenter type (Indenter Type).

Hardness Value (Hardness Value) and Standard Deviation (Standard Deviation).

Test date (Date / Test date), operator (Operator / Operator) and equipment number (Equipment Number / Equipment Number).

Example: WC-Co coating, Vickers hardness HV 1200 ± 20 (load 5 N).

9. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <3%, Between Laboratories (Between Laboratories / Between Laboratories) <5%.

Bias: May be caused by surface unevenness or load deviation, requiring control of surface quality and equipment calibration.

10. Annexes

Annex A: Hardness Conversion Table, refer to ISO 18265.

Appendix B: Indentation Measurement Diagram .

11. Applicability and Limitations

Applicability: Suitable for hardness testing of metallic materials and thermal spray coatings, widely used in quality control.

Limitations:

Not suitable for non-metallic materials (such as ceramics, unsintered).

Thin coatings < 0.5 mm thick should be used with caution and a Micro-Load may be required.

appendix:

ISO 9227:2017 Corrosion tests in artificial atmospheres
— Salt spray tests
Corrosion testing in artificial atmospheres
— Salt spray test

1. Scope

1.1 This International Standard specifies the method for conducting salt spray tests (Salt Spray Tests / Salt Spray Tests) in artificial atmospheres (Artificial Atmospheres / Artificial Atmospheres) for evaluating the corrosion resistance (Corrosion Resistance / Corrosion Resistance) of metallic materials and their coatings.
Applicable Objects: including metallic materials, thermally sprayed coatings (such as WC-Co cemented carbide/Cermet Coating), electroplated coatings and organic coatings.
Purpose: To evaluate the corrosion resistance of materials or coatings by simulating a salt spray environment for quality control and performance verification.

1.2 This standard includes three test methods:
Neutral Salt Spray Test (NSS / Neutral Salt Spray Test, NSS).
Acetic Acid Salt Spray Test (AASS).
Copper-Accelerated Acetic Acid Salt Spray Test (CASS).

1.3 This standard is not intended to predict the long-term corrosion resistance of materials in actual environments and is intended only for laboratory comparison tests.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
ISO 1514:2016 - Paints and varnishes — Standard panels for testing
ISO 2808:2019 - Paints and varnishes — Determination of film thickness
ISO 3574:2012 - Cold-reduced carbon steel sheet of commercial and drawing qualities
ISO 8044:2015 - Corrosion of metals and alloys — Basic terms and definitions
ISO 8407:2021 - Corrosion of metals and alloys — Removal of corrosion products from corrosion test specimens
Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, some of which refer to ISO 8044:
Salt Spray: An aerosol formed by the atomization of a salt solution (Salt Solution), used to simulate a corrosive environment.
Corrosion Resistance: The ability of a material or coating to resist corrosion, usually assessed by the extent of formation of corrosion products.
Specimen: Test specimen used for salt spray test.

NSS (Neutral Salt Spray): Salt spray test using neutral salt solution (pH 6.5-7.2).
AASS (Acetic Acid Salt Spray): A salt spray test in which acetic acid is added to lower the pH value (3.1-3.3).
CASS (Copper-Accelerated Acetic Acid Salt Spray): A salt spray test that adds copper chloride (Copper Chloride) to AASS to accelerate corrosion.

4. Principles of Test

The specimen is exposed to a salt spray environment (Salt Spray Environment / Salt Spray Environment), and a uniform corrosive aerosol (Corrosive Aerosol / Corrosive Aerosol) is formed by atomization of the salt solution (Salt Solution / Salt Solution).
The extent of corrosion is assessed by observing the formation of corrosion products (Corrosion Products / Corrosion Products), mass loss (Mass Loss / Mass Loss) or surface defects (Surface Defects / Surface Defects).

5. Test Apparatus

Salt Spray Chamber (Salt Spray Chamber):
Capacity: ≥400 L, ensuring uniform atomization.
Material: Corrosion-resistant materials, such as fiberglass reinforced plastic (Fiberglass Reinforced Plastic).
Nozzle: Non-metallic material, produces uniform fine mist (Fine Mist).
Temperature Control: The temperature in the test chamber is maintained at 35±2°C.
Collection Device: At least 2 collection funnels to measure the Salt Spray Deposition Rate.

6. Test Solution

Salt Solution:
Ingredients: Sodium Chloride (NaCl / sodium chloride) concentration 50±5 g/L.
Purity: NaCl impurity <0.5%, does not contain copper and nickel.
Water Quality: Distilled or Deionized Water, conductivity <20 µS /cm.
pH Value:
NSS: 6.5-7.2.
AASS: 3.1-3.3 (adjusted by adding acetic acid).
CASS: 3.1-3.3 (add 0.26±0.02 g/L copper chloride).

7. Specimen Preparation

Specimen Dimensions: Recommended 150 mm × 100 mm × Thickness, in accordance with ISO 1514.
Preparation :
Removes oil stains (Contaminants / Oil stains) and oxide scale (Oxide Scale / Oxide Scale).
Thermal spray coating: surface roughness Ra 3-5 µm , in accordance with ISO 8501-1.
Quantity: ≥3 specimens per group, representative testing.
Positioning: The specimen should be placed at an angle of 15°-30° to the vertical to avoid direct spraying.

8. Test Conditions

Temperature: 35±2°C in the test chamber.

Salt Spray Deposition Rate: 1-2 mL/(80 cm² · h).

Test Duration:

NSS: 24 h, 48 h, 96 h, 240 h, 480 h or 720 h.

AASS and CASS: 24 h, 48 h, or 96 h.

Humidity: Relative Humidity: 95%-100%.

9. Test Procedure

Preparation

Prepare salt solution and adjust pH.

Preheat test chamber to 35°C.

Testing:

Place the sample in the test chamber and start the salt spray.

Check sedimentation rate and temperature every 24 hours.

Completion:

After the test, the sample is washed with distilled water to remove salt (Salt Deposits).

Removal of corrosion products (Corrosion Products / Corrosion Products) according to ISO 8407.

10. Evaluation Methods

Visual Inspection: Observe the distribution of corrosion products, rust spots and coating peeling.

Mass Loss: The mass loss of a sample before and after the test is measured in g/ m² .

Corrosion Rating: Assessed according to ISO 8407, such as No Corrosion, Slight Corrosion, etc.

11. Test Report

Contents

Specimen Material and coating information (e.g. WC-Co coating, Steel Substrate).

Test Method (Test Method, such as NSS).

Test Conditions: Temperature, sedimentation rate, time.

Evaluation Results: Corrosion degree, mass loss, photos.

Test Date (Date / Test Date), Operator (Operator / Operator) and Equipment Number (Equipment Number / Equipment Number).

Example: WC-Co coating, NSS test 480 h, surface slight corrosion (Slight Corrosion), mass loss 2.5 g/ m² .

12. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <10%, Between Laboratories (Between Laboratories / Between Laboratories) <15%.

Bias: May be affected by the uniformity of the spray or the position of the specimen, and the spray distribution needs to be controlled.

13. Annexes

Appendix A (Annex A): Salt Spray Chamber Design Guidelines (Salt Spray Chamber Design Guidelines).

Appendix B (Annex B / Appendix B): Standard Reference Materials (Standard Reference Materials / Standard Reference Materials).

14. Applicability and Limitations

Applicability: Applicable to corrosion resistance testing of metal materials and coatings, widely used in quality control.

Limitations:

Not suitable for predicting long-term corrosion resistance in actual environments.

Use caution with non-metallic coatings and adjustment of test conditions may be necessary.

Summary

ISO 9227:2017 "Corrosion tests in artificial atmospheres — Salt spray tests" provides standard methods for salt spray tests (NSS, AASS, CASS), which are suitable for evaluating the corrosion resistance of metallic materials and thermal spray coatings (such as cemented carbide coatings).

appendix:

ASTM B665-01(2014)
Standard Guide for Metallographic Identification of Microstructure in Cemented Carbides
Standard guide for metallographic identification of cemented carbide microstructures

1. Scope

1.1 This standard guide specifies metallographic identification methods for the microstructure of cemented carbides for both quality control and research purposes.
Applicable Objects: Tungsten carbide (WC) based cemented carbide (such as WC-Co), titanium carbide (TiC) and tantalum carbide (TaC) composite materials are widely used in thermal spray coatings (Thermal Sprayed Coatings) and cutting tools.
Purpose: To provide a standardized method for characterizing microstructures and identifying phase structure, porosity, and defects.

1.2 This specification applies to sintered (sintered) or thermally sprayed (thermally sprayed) cemented carbides.

1.3 This standard does not cover mechanical property testing (Mechanical Property Testing) of cemented carbide.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
ASTM E3-11(2017) - Standard Guide for Preparation of Metallographic Specimens
ASTM E7-15 - Standard Terminology Relating to Metallography
ASTM E407-07(2015)e1 - Standard Practice for Microetching Metals and Alloys
Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, referring to ASTM E7:
Cemented Carbide: A composite material made of carbides (such as WC) and a metal binder phase (such as Co) by sintering.
Microstructure: The internal phase structure and defect characteristics of a material observed under a microscope.
Porosity: The voids in cemented carbide are divided into Type A (Small Pores), Type B (Medium Pores) and Type C (Large Pores).
Binder Phase (Binder Phase): Such as Cobalt (Cobalt) or Nickel (Ni), which binds the carbide particles.
Etching: Process of revealing microstructural features by chemical or electrochemical means.

4. Principles of Microstructure Identification

Through metallographic preparation (Metallographic Preparation / Metallographic Preparation) and etching (Etching / Etching), the phase structure (Phase Structure / Phase Structure), grain size (Grain Size / Grain Size) and defects (Defects / Defects) of cemented carbide are observed using an optical microscope (Optical Microscope / Optical Microscope) or a scanning electron microscope (SEM / Scanning Electron Microscope).

5. Specimen Preparation

Sectioning: Use a diamond saw and avoid overheating.
Grinding: Use SiC sandpaper (Silicon Carbide Paper), from coarse (#120) to fine (#1200).
Polishing: Use diamond suspension (diamond suspension, particle size 1 μm) to a mirror finish.
Etching:
Recommended reagent: Murakami reagent (10 g $K_3[Fe(CN)_6]$ + 10 g KOH + 100 mL H_2O), etching time 5-15 seconds.
Alternative method: Electrolytic Etching (Electrolytic Etching) using 10% HCl solution.
Cleaning: Clean with ethanol (Ethanol), dry (Dry).

6. Microscopic Examination

Equipment: Optical microscope (Magnification 50-1000 times) or SEM.
Observation Parameters
Carbide Grain Size: Measured according to ASTM E112.
Porosity: Classified into types A, B, and C, refer to ISO 4505.
Defects: such as cracks and inclusions.
Magnification: 100-500 times is recommended, depending on the particle size.

7. Microstructure Classification

Phase Structure
WC-Co: tungsten carbide particles (WC Grains / tungsten carbide particles) and cobalt binder (Co Binder / cobalt binder).
Multi-Phase Alloys: Contains TiC or TaC .
Grain Size Grade:
Ultra-Fine: ≤0.5 μm .
Fine: 0.5-2 μm .
Medium: 2-5 μm .
Coarse: >5 μm .
Porosity Grade:
A00-A04: Small Pores.
B00-B04 : Medium Pores (Medium Pores / Medium Pores).
C00-C04: Large Pores.

8. Report

Contents

Specimen Material: such as WC-12Co coating, substrate.

Preparation Method: such as thermal spraying (HVOF).

Microstructure Features: Grain size, porosity, defects.

Etching Conditions: Reagents and time.

Photographs and Magnification.

Test date (Date / Test date), operator (Operator / Operator) and equipment number (Equipment Number / Equipment Number).

Example: WC-12Co coating, grain size 2 µm , porosity grade A02, magnification 200x, no cracks.

9. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <5%, Between Laboratories (Between Laboratories / Between Laboratories) <10%.

Bias: May be caused by uneven preparation or over-etching. Preparation quality needs to be controlled.

10. Annexes

Appendix A: Murakami Reagent Preparation.

Appendix B: Microscopic Examination Examples.

11. Applicability and Limitations

Applicability: Suitable for quality control and research of cemented carbide microstructures, especially for thermal spray coatings.

Limitations:

Not suitable for non-carbide materials.

For ultra-thin coatings (<0.1 mm), the preparation method needs to be adjusted.

Summary

ASTM B665-01(2014)《Standard Guide for Metallographic Identification of Microstructure in Cemented Carbides / Standard Guide for Metallographic Identification of Microstructure in Cemented Carbides》 provides methods for microstructural identification of cemented carbides (such as thermal sprayed WC-Co coatings), including preparation, corrosion, and microscopic examination, which is suitable for quality control and research.

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appendix:

ASTM E2283-08(2019)
Standard Practice for Extreme Value Analysis of Nonmetallic Inclusions in Steel and Other Microstructural Features
Standard practice for extreme value analysis of nonmetallic inclusions in steel and other microstructural features

1. Scope

1.1 This standard practice provides a method for estimating the maximum size (maximum size) of nonmetallic inclusions (Nonmetallic Inclusions) or other microstructural features (Microstructural Features) in steel using extreme value statistical analysis.
Applicable Objects: Steel, Cemented Carbides (such as WC-Co thermal spray coatings), and other metal materials, with a focus on analyzing non-metallic inclusions, porosity, or microdefects.
Purpose: To predict the size of the largest inclusion or defect in a material by statistical methods for evaluating material properties (such as fatigue life) and quality control.

1.2 This standard applies to the microstructural features observed by metallographic microscope (Metallographic Microscopy).

1.3 This standard does not involve mechanical property testing (Mechanical Property Testing / Mechanical Property Testing) and only provides statistical analysis methods.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
ASTM E3-11(2017) - *Standard Guide for Preparation of Metallographic Specimens*
ASTM E7-15 - *Standard Terminology Relating to Metallography*
ASTM E45-18 - *Standard Test Methods for Determining the Inclusion Content of Steel*
ASTM E112-13 - *Standard Test Methods for Determining Average Grain Size*
Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, referring to ASTM E7:
Nonmetallic Inclusions: Nonmetallic phases (such as oxides, sulfides) in steel or other metal materials.
Extreme Value Analysis: A statistical method used to predict the distribution of the largest size inclusions or defects in a sample.
Control Area: The measurement area defined in microscope observation, in mm^2 .
Maximum Size: The maximum linear dimension of an inclusion or defect, in μm .
Gumbel Distribution: A statistical distribution model used for extreme value analysis.

4. Principles of Extreme Value Analysis

Metallographic Observation is used to measure the size of the largest inclusion or defect within multiple control areas.

Fit the data using the Gumbel Extreme Value Distribution (Gumbel Extreme Value Distribution) to predict the likely size of the largest inclusion or defect in a larger volume of material.

5. Specimen Preparation

Sectioning: Use a diamond saw to avoid introducing additional defects.

Grinding: Use SiC sandpaper (Silicon Carbide Paper), from coarse (#120) to fine (#1200).

Polishing: Use diamond suspension (diamond suspension, particle size 1 μm) to a mirror finish.

Etching (optional): Use a suitable reagent (e.g. 2% nitric acid/Nital for steel) to reveal inclusions or microstructure.

Cleaning: Clean with ethanol (Ethanol), dry (Dry).

6. Measurement Procedure

Equipment: Optical Microscope or Scanning Electron Microscope (SEM), Magnification 100-500x.

Control Area:

For each specimen, measure at least 30 control areas (Minimum 30 Areas).

Recommended area: 0.1 mm² to 1 mm² , depending on inclusion density.

Measurement:

Within each control area, record the size of the largest inclusion or defect (Maximum Inclusion Size).

Measure the maximum linear dimension of the inclusion (Maximum Linear Dimension / Maximum Linear Dimension) in μm .

Recording: Arranges the largest size data in ascending order in preparation for extreme value analysis.

7. Extreme Value Analysis Method

Data Fitting:

Fit the maximum size data to a Gumbel distribution (Gumbel Distribution / Gumbel Distribution).

Gumbel distribution cumulative distribution function:

$F(x) = \exp(-\exp(-(x-\lambda)/\delta))$

where λ is the location parameter and δ is the scale parameter.

Parameter Estimation

Estimate λ and δ using the Maximum Likelihood Method (MLM) or the Least Squares Method (Least Squares Method).

Prediction:

Calculates the maximum inclusion size in a specified volume (Specified Volume) at a specified confidence level (e.g. 95%).

Formula: $x\_p = \lambda - \delta \times \ln(-\ln(p))$, where p is probability (Probability / probability).

8. Report

Contents

Specimen Material: For example, Steel or WC-Co coating.

Preparation Method: such as thermal spraying (HVOF).

Control Area (Control Area) and Number of Measurements (Number of Measurements).

Maximum Size Data (Maximum Size Data / Maximum Size Data) and Gumbel distribution parameters (Gumbel Parameters / Gumbel parameters).

Predicted Maximum Inclusion Size.

Photographs and Magnification.

Test date (Date / Test date), operator (Operator / Operator) and equipment number (Equipment Number / Equipment Number).

Example: WC-Co coating, control area 0.5 mm² , 30 zones, predicted maximum inclusion size 50 μm (95% confidence level), magnification 200x.

9. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <10%, Between Laboratories (Between Laboratories / Between Laboratories) <15%.

Bias: May be caused by uneven sample preparation (Preparation Unevenness) or uneven inclusion distribution (Inclusion Distribution), and requires increasing the number of measurement areas.

10. Annexes

Appendix A: Gumbel Distribution Fitting Example.

Appendix B: Inclusion Size Measurement Guidelines.

11. Applicability and Limitations

Applicability: Suitable for extreme value analysis of inclusions or defects in steel, cemented carbide and other materials. Widely used in quality control and fatigue analysis.

Limitations:

A sufficient number of control areas is required to ensure statistical reliability.

Not suitable for materials with Very Low Inclusion Density.

Summary

ASTM E2283-08(2019) "Standard Practice for Extreme Value Analysis of Nonmetallic Inclusions in Steel and Other Microstructural Features / Standard Practice for Extreme Value Analysis of Nonmetallic Inclusions in Steel and Other Microstructural Features" provides a method for evaluating the maximum inclusion or defect size in steel or cemented carbide (such as thermal sprayed WC-Co coating) using extreme value statistical analysis, which is suitable for quality control and performance evaluation.

appendix:

EN 13204:2017

Thermal spraying — Powders — Composition, technical supply conditions

Thermal spraying - Powders - Composition, technical supply conditions

1. Scope

1.1 This standard specifies the composition (Composition / composition) and technical supply conditions (Technical Supply Conditions / technical supply conditions) of powders (Powders / Powders) used in the thermal spraying process.

Applicable Objects: including Metallic Powders (such as Nickel and Cobalt), Ceramic Powders (such as Alumina), Carbide Powders (such as WC-Co Cermet) and Composite Powders.

Purpose: To ensure powder meets Thermal Spraying Process Requirements for quality control and performance optimization.

1.2 This standard applies to flame spraying, plasma spraying, HVOF and other processes.

1.3 This standard does not cover the powder manufacturing process (Powder Manufacturing Process / Powder Preparation Process), but only specifies the supply conditions.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:

EN 657:2005 - *Thermal spraying — Terminology, classification*

EN 820-1:2002 - *Advanced technical ceramics — Methods of testing monolithic ceramics — Part 1: Determination of density and porosity*

EN ISO 3252:1999 - *Powder metallurgy — Vocabulary*

Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, referring to EN 657 and EN ISO 3252:

Thermal Spraying Powder: Granular material used in thermal spraying process.

Particle Size Distribution: The range and proportion of powder particle diameters, expressed in µm .

Chemical Composition: The content of each element in the powder, expressed in wt %.

Flowability: The time it takes for a powder to pass through a standard funnel under specified conditions, expressed in seconds per 50g.

Apparent Density: The density of a powder in a loose state, expressed in g/ cm³ .

4. Technical Requirements

4.1 Chemical Composition/Chemical Composition

Requirements:

The content of each element must comply with the order specifications (Order Specifications).

Impurities (Impurities) content ≤ 0.5% (unless otherwise specified).

Test Methods

Spectroscopic Analysis (Refer to EN ISO 10378).

Oxygen/Nitrogen Content: Measured using the Fusion-Infrared Method.

4.2 Particle Size Distribution

Requirements:

The particle size range (Particle Size Range / Particle Size Range) is specified by the ordering party, such as 10-45 μm , 15-53 μm .

The particle size distribution must be uniform (Uniform Distribution / Uniform Distribution) and comply with the sieve test (Sieve Analysis / Sieve Test).

Test Methods

Laser Diffraction Analysis (Laser Diffraction Analysis, see EN ISO 13320).

Standard Sieving / Standard Sieving.

4.3 Flowability

Requirements:

Fluidity ≤30 s/50g (specific value specified by the ordering party).

Test Methods

Use a Hall Flowmeter (refer to EN ISO 4490).

4.4 Apparent Density

Requirements:

The apparent density range is specified by the ordering party, e.g. 2.5-4.5 g/cm³ (depending on the powder type).

Test Methods

Hall Flow Cup Method (Hall Flow Cup Method , refer to EN ISO 3923-1).

4.5 Morphology and Purity

Requirements:

Powder Morphology is either spherical or irregular, depending on the process.

Purity: ≥99% (unless otherwise specified).

Test Methods

Scanning electron microscopy (SEM/scanning electron microscope) was used to observe the morphology.

X-ray fluorescence (XRF / X-ray Fluorescence) detection of impurities.

5. Packaging and Marking

Packaging :

Use sealed containers such as plastic buckets or metal cans to prevent moisture and contamination.

Net Weight: 5 kg, 10 kg or as per order requirement.

Marking:

Product Name: For example, WC-12Co.
Batch Number (Batch Number) and Production Date (Production Date).
Manufacturer's Name (Manufacturer's Name) and Safety Instructions (Safety Instructions).

6. Inspection and Testing

Inspection Types:
Type Inspection: For new products or new batches.
Batch Inspection: Each batch of products.
Test Methods
Determination of density and porosity with reference to EN 820-1.
Chemical composition analysis according to EN ISO 10378.
Sampling:
The sample quantity of each batch (Sample Quantity / Sampling Volume) is ≥ 200 g, in accordance with EN ISO 14284.

7. Report

Contents
Product Description: Such as WC-12Co powder.
Chemical Composition: C 5.2%, Co 12.0%.
Particle Size Distribution: 10-45 μm .
Flowability: 25 s/50g.
Apparent density: 4.0 g/ cm^3 .
Inspection Date (Inspection Date), Batch Number (Batch Number) and Manufacturer Information (Manufacturer Information).
Example
WC-12Co powder, C 5.2%, particle size 10-45 μm , flowability 24 s/50g, meets EN 13204:2017 requirements.

8. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <5%, Between Laboratories (Between Laboratories / Between Laboratories) <10%.
Bias: May be due to sample representativeness or test condition variations, requiring strict control of sampling and testing.

9. Applicability and Limitations

Applicability: Suitable for the supply and quality control of thermal spray powders, especially for cemented carbide powders (such as WC-Co).
Limitations:
No powder preparation process is involved.
Additional Agreement is required for powders for special purposes.

Summary

EN 13204:2017 Thermal spraying — Powders — Composition, technical supply conditions provides the composition and supply condition requirements for thermal spraying powders (such as WC-Co cemented carbide powders), including chemical composition, particle size distribution and fluidity, which is suitable for quality control and process optimization.

appendix:

GB/T 5242-2007
Thermal spraying — Wire and rods
Thermal Spray - Wire and Rod

1. Scope

1.1 This standard specifies the technical requirements, inspection rules, and delivery conditions for wires and rods used in the thermal spraying process .

Applicable Objects: including pure metal wires (such as zinc, aluminum), alloy wires (such as nickel-based, cobalt -based) and composite materials (such as WC-Co cemented carbide/WC-Co Cermet related wires).

Purpose: To ensure that wires and rods meet the requirements of thermal spraying processes (such as flame spraying, plasma spraying) for quality control and performance assurance.

1.2 This standard applies to processes such as arc spraying (Arc Spraying / Arc Spraying) and flame spraying (Flame Spraying / Flame Spraying).

1.3 This standard does not cover the manufacturing process for wire and rods . It only specifies technical specifications and inspection requirements.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:

GB/T 1267-2007 - *Methods for sampling steel and cast iron — Cut-up testing and analysis / Steel and cast iron sampling methods — Cut-up testing and analysis*

GB/T 223 - *Methods for chemical analysis of iron, steel and alloy / Chemical analysis methods of iron, steel and alloy*

GB/T 4340.1-2009 - *Metallic materials — Vickers hardness test — Part 1: Test method*

Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions:

Wire: A continuous filament with a diameter of 0.8-4.0 mm used for thermal spraying.

Rod: A short rod or bar with a diameter of 4.0-10.0 mm.

Chemical Composition: The content of each element in a metal wire or rod, expressed in wt %.

Surface Quality: Surface cleanliness and defects (such as cracks and scratches).

Hardness: The material's ability to resist local plastic deformation, measured in HV.

4. Technical Requirements

4.1Chemical Composition/Chemical Composition

Requirements:

The content of each element must comply with the order specifications (Order Specifications).

Impurities (Impurities) content ≤ 0.5% (unless otherwise specified).

Test Methods

Spectroscopic Analysis (Spectroscopic Analysis / Spectroscopic Analysis, refer to GB/T 223).

Oxygen/Nitrogen Content: Fusion-Infrared Method.

4.2 Dimensions and Tolerances

Diameter:

Metal wire: 0.8-4.0 mm, tolerance ±0.05 mm.

Rod: 4.0-10.0 mm, tolerance ±0.1 mm.

Length (Length / Length):

Wire: Available in continuous supply or in ordered lengths.

Rod: 500-1000 mm, tolerance ±5 mm.

Test Methods

Measure with a Vernier Caliper (Vernier Caliper) or a Micrometer (Micrometer).

4.3 Surface Quality

Requirements:

There are no cracks (Cracks / Cracks), scratches (Scratches / Scratches) or oxide scale (Oxide Scale / Oxide Scale) on the surface.

Cleanliness (Cleanliness) complies with GB/T 1267.

Test Methods

Visual Inspection (Visual Inspection) or Low-Power Magnifier (Low-Power Magnifier).

4.4 Hardness

Requirements:

The hardness range is specified by the ordering party, such as HV 200-600 (depending on the material).

Test Methods

Vickers Hardness Test (Vickers Hardness Test / Vickers Hardness Test, refer to GB/T 4340.1), load 5-10 N.

4.5 Straightness

Requirements:

Bending per Meter ≤ 1 mm.

Test Methods

Place it on a flat surface and measure the maximum deviation.

5. Packaging and Marking

Packaging:

Use moisture-proof packaging such as plastic bags or airtight containers.

each coil or bundle is 5-20 kg or as per order.

Marking:

Product Name: Such as NiAl wire.

Batch Number (Batch Number / Batch Number), Production Date (Production Date / Production Date).

Manufacturer's Name (Manufacturer's Name) and Safety Instructions (Safety Instructions).

6. Inspection and Testing

Inspection Types:

Type Inspection: For new products or new batches.

Batch Inspection: Each batch of products.

Test Methods

Chemical composition is in accordance with GB/T 223.

Dimensions and surface quality are determined by visual inspection and measuring tools.

Hardness is in accordance with GB/T 4340.1.

Sampling:

The sampling quantity of each batch (Sample Quantity / Sampling Quantity) ≥ 1 m (wire) or 1 piece (rod), in accordance with GB/T 1267.

7. Report

Contents

Product Description: NiAl wire, diameter 1.6 mm.

Chemical Composition: Ni 50%, Al 50%.

Dimensions: Diameter 1.60 ± 0.05 mm.

Hardness: HV 250±20.

Surface Quality: No defects.

Inspection Date (Inspection Date), Batch Number (Batch Number) and Manufacturer Information (Manufacturer Information).

Example

NiAl wire, diameter 1.6 mm, chemical composition Ni 50.2%, Al 49.6%, hardness HV 245, surface defect-free, in line with GB/T 5242-2007.

8. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <5%, Between Laboratories (Between Laboratories / Between Laboratories) <10%.

Bias: May be due to sample representativeness or test condition variations, requiring sampling and environmental control.

9. Applicability and Limitations

Applicability: Suitable for the supply and quality control of wires and rods for thermal spraying , especially for cemented carbide related materials.

Limitations:

No manufacturing process involved.

For special purpose wires , an additional agreement is required.

Summary

GB/T 5242-2007 "Thermal spraying — Wire and rods / Thermal spraying — Metal wires and rods" provides technical requirements and inspection rules for metal wires and rods for thermal spraying (such as NiAl or WC-Co related materials), which is applicable to quality control and process applications.

appendix:

GB/T 3489-2012

Thermal spraying — Metallographic examination of thermal spray coatings
Thermal Spraying - Metallographic Inspection of Thermal Sprayed Coatings

1. Scope

1.1 This standard specifies methods for metallographic examination of thermal spray coatings for use in quality control and performance evaluation.
Applicable Objects: including Metallic Coatings (such as Nickel and Cobalt), Ceramic Coatings (such as Alumina) and Carbide Coatings (such as WC-Co Cermet).
Purpose: To evaluate the microstructure, porosity, bond strength and defects of coatings by microscopic observation.

1.2 This standard applies to flame spraying, plasma spraying and HVOF processes.

1.3 This standard does not cover mechanical property testing of coatings, but only provides metallographic examination methods.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
GB/T 1267-2007 - *Methods for sampling steel and cast iron — Cut-up testing and analysis / Steel and cast iron sampling methods — Cut-up testing and analysis*
GB/T 13298-2015 - *Inspection methods of microstructure for metals*
GB/T 4338-2006 - *Metallic materials — Tensile testing at ambient temperature*
Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard adopts the following terms and definitions, with reference to GB/T 13298:
Thermal Spray Coating: A coating deposited on a substrate by a thermal spraying process.
Microstructure: Phase structure, grain size and defect characteristics in the coating.
Porosity: The volume percentage of pores (Pores) in a coating, expressed in %.
Bond Interface: The connecting area between the coating and the substrate.
Etching: Process of revealing microstructure by chemical or electrochemical means.

4. Specimen Preparation

Sectioning:
Use a diamond saw to cut and avoid overheating or damage.
Specimen Size: 20 mm × 10 mm × coating thickness + 5 mm is recommended.
Mounting:
Embed with epoxy resin (Epoxy Resin / Epoxy Resin) or phenolic resin (Phenolic Resin / Phenolic

Resin) to protect the coating edge (Coating Edge / Coating Edge).

Grinding:

Use SiC sandpaper (Silicon Carbide Paper / Silicon Carbide Sandpaper), from coarse (#120) to fine (#1200).

Polishing:

Use diamond suspension (Diamond Suspension / Diamond Suspension, particle size 1 μm) to a mirror finish (Mirror Finish / Mirror Finish).

Etching:

Metal coating: 2% nitric acid (Nital / nitric acid), corrosion time 5-10 seconds.

Ceramic/carbide coatings: Murakami reagent (10 g K_3 [Fe(CN) $_6$] + 10 g KOH + 100 mL H_2O) , etching time 10-20 seconds.

5. Microscopic Examination

Equipment:

Optical Microscope (Optical Microscope / Optical Microscope), Magnification (Magnification / Magnification) 50-1000 times.

Scanning Electron Microscope (SEM / Scanning Electron Microscope) for High-Resolution Observation (High-Resolution Observation / High-Resolution Observation).

Observation Parameters

Microstructure: Phase Distribution, Grain Size.

Porosity: calculated by Image Analysis (Image Analysis), unit: %.

Bond Interface: Observe for cracks (Cracks) or unfused areas (Unbonded Areas).

Defects: Such as inclusions and gas pores.

Magnification:

Overall Structure: 50-200 times.

Details: 500-1000 times.

6. Evaluation Criteria

Porosity:

Metal coating: ≤5% (recommended value).

Ceramic/carbide coating: ≤2% (recommended value).

Bond Quality:

There are no continuous cracks at the bonding interface (No Continuous Cracks).

Unbonded Area (Unbonded Area) ≤ 5%.

Defect Rating :

Minor: Scattered small defects.

Severe: Extensive cracking or loss.

7. Report

Contents

Coating Material: such as WC-12Co.

Preparation Method: Such as HVOF thermal spraying.

Microstructure: phase distribution, particle size.

Porosity: For example, 1.5%.

Bond Interface: No cracks.

Defects: No serious defects.

Photographs and Magnification.

Inspection Date (Inspection Date), Operator (Operator) and Equipment Number (Equipment Number).

Example

WC-12Co coating, HVOF spraying, porosity 1.2%, no cracks at the bonding interface, magnification 200 times, no serious defects.

8. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <5%, Between Laboratories (Between Laboratories / Between Laboratories) <10%.

Bias: May be caused by uneven sample preparation (Preparation Unevenness) or over-etching (Over-Etching), and the preparation process needs to be controlled.

9. Applicability and Limitations

Applicability: Suitable for metallographic examination of thermal spray coatings (such as WC-Co cemented carbide coatings), widely used in quality control and research.

Limitations:

Not suitable for non-thermal spray coatings.

For ultra-thin coatings (<0.1 mm), the preparation method needs to be adjusted.

Summary

GB/T 3489-2012 "Thermal spraying — Metallographic examination of thermal spray coatings / Thermal spraying — Metallographic examination of thermal spray coatings" provides metallographic examination methods for thermal spray coatings (such as WC-Co cemented carbide coatings), including preparation, observation and evaluation, which is suitable for quality control and performance evaluation.

appendix

GB/T 38511-2020
Thermal spraying — Powders
— Composition, technical supply conditions

Thermal spraying - Powders - Composition, technical supply conditions

1. Scope

1.1 This standard specifies the composition, characteristics, and technical supply conditions of powders used in the thermal spraying process.
Applicable Objects: including Metallic Powders (such as Nickel-Based, Cobalt -Based), Ceramic Powders (such as Alumina), Carbide Powders (such as WC-Co Cermet) and Composite Powders.
Purpose: To ensure that the powder meets the Thermal Spraying Process Requirements for quality control and coating performance optimization.

1.2 This standard applies to processes such as plasma spraying (Plasma Spraying), flame spraying (Flame Spraying), and HVOF (High-Velocity Oxygen Fuel) processes.

1.3 This standard does not cover the powder manufacturing process (Powder Manufacturing Process / Powder Manufacturing Process), but only specifies its supply conditions and acceptance criteria.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
GB/T 1480-2010 - Metallic powders — Determination of particle size by dry sieving
GB/T 1482-2010 - Metallic powders — Determination of flow time by means of a calibrated funnel (Hall flowmeter) / Metallic powders — Determination of flow time by means of a calibrated funnel (Hall flowmeter)
GB/T 31561-2015 - Metallic powders — Determination of apparent density
GB/T 19077-2016 - Particle size distribution — Laser diffraction methods
Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions:
Thermal Spraying Powder: Granular material used in thermal spraying process.
Chemical Composition: The mass percentage of each element in the powder, expressed in wt %.
Particle Size Distribution: The range and proportion of powder particle diameters, expressed in μm .
Flowability: The time it takes for a powder to pass through a calibrated funnel (measured in seconds per 50 g).

Apparent Density: The density of a powder in a loose state, expressed in g/ cm^3 .

Particle Morphology: The shape of powder particles, such as spherical or irregular.

4. Classification

By Material Type:

Metallic Powders: such as NiCr and CoCr.

Ceramic Powders : such as Al_2O_3 and ZrO_2 .

Carbide powders: such as WC-Co, Cr_3C_2 - NiCr .

Composite Powders: such as Ni-Al_2O_3 .

By Particle Size Range:

Fine powder: 5-25 μm .

Medium Powder: 25-45 μm .

Coarse Powder: 45-90 μm .

5. Technical Requirements

5.1 Chemical Composition/Chemical Composition

Requirements:

The content of each element must comply with the order specifications (Order Specifications).

Main Component Deviation: ±0.5% (unless otherwise specified).

Impurities: ≤ 0.3% (unless otherwise specified).

Test Methods

Chemical Analysis: such as ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry).

Oxygen/Nitrogen Content: Fusion-Infrared Method.

5.2 Particle Size Distribution

Requirements:

The particle size range must meet the ordering specifications, such as 10-45 μm .

Particle size distribution deviation (Distribution Deviation): ±10% (D10, D50, D90).

Test Methods

Laser Diffraction Method (Laser Diffraction Method, refer to GB/T 19077).

Dry Sieving (Dry Sieving / Dry Sieving, refer to GB/T 1480).

5.3 Flowability

Requirements:

Fluidity ≤35 s/50g (specific value specified by the ordering party).

For fine powders (<25 μm), flowability may not be required (Not Required).

Test Methods

Hall flowmeter (Hall Flowmeter, refer to GB/T 1482).

5.4 Apparent Density

Requirements:

The apparent density range is specified by the ordering party, e.g. 2.0-5.0 g/cm³ (depending on the powder type).

Deviation: ±0.2 g/ cm³ .

Test Methods

Apparent density determination (Apparent Density Determination / Apparent density determination, refer to GB/T 31561).

5.5 Particle Morphology

Requirements:

The particle shape must meet the order specifications, spherical (Spherical / spherical) or near-spherical (Near-spherical / near-spherical) is recommended.

The proportion of irregular particles (Irregular Particles / irregular particles) is ≤10%.

Test Methods

Scanning electron microscope (SEM/scanning electron microscope) observation.

5.6 Moisture Content

Requirements:

Moisture content ≤0.2%.

Test Methods

Drying Loss Method: Dry at 105°C for 2 hours and weigh.

6. Inspection Rules

Inspection Types:

Factory Inspection: Each batch of products.

Type Inspection: When new products or process changes.

Sampling:

The sampling quantity of each batch (Sample Quantity / Sampling Quantity) is ≥200 g, and the samples are divided after uniform mixing.

Sampling method: Refer to GB/T 1267.

Judgment Rules

All projects meet the requirements and are qualified.

If any item fails, the entire batch will be considered unqualified (Unqualified / Unqualified), and re-sampling and re-inspection (Re-Inspection / Re-inspection) may be required.

7. Packaging, Transportation, and Storage

Packaging:

Use sealed containers, such as plastic buckets or metal cans, to prevent moisture (moisture-proof / moisture-proof) and contamination (contamination-proof / contamination-proof).

Weight : 5 kg, 10 kg or as per order requirement.

Marking:

Product Name: Such as WC-12Co powder.

Batch Number (Batch Number / Batch Number), Production Date (Production Date / Production

Date).

Manufacturer's Name (Manufacturer's Name) and Safety Instructions (Safety Instructions).

Transportation:

Avoid severe vibration (Severe Vibration / Severe Vibration) and humid environment (Humid Environment / Humid Environment).

Storage:

Store in a dry and ventilated environment (Dry and Ventilated Environment / Dry and ventilated environment), temperature <30°C, humidity <60%.

Storage Period: Not more than 12 months.

8. Quality Certificate

Contents

Product Name (Product Name) and Specification (Specification).

Batch Number (Batch Number) and Production Date (Production Date).

Inspection Results: Chemical composition, particle size distribution, fluidity, apparent density, etc.

Declaration of Compliance: In accordance with GB/T 38511-2020.

Manufacturer Information (Manufacturer Information / Manufacturer Information) and Inspector's Signature (Inspector 's Signature / Inspector's Signature).

9. Precision and Bias

Precision: Within Laboratory (Within Laboratory / Within Laboratory) deviation <5%, Between Laboratories (Between Laboratories / Between Laboratories) <8%.

Bias: may be caused by sampling unevenness or test equipment variation, and the test conditions must be strictly controlled.

10. Applicability and Limitations

Applicability: Suitable for the supply and quality control of thermal spray powders, especially for cemented carbide powders such as WC-Co.

Limitations:

No powder manufacturing process is involved.

Additional Agreement is required for powders for special purposes.

Summary

GB/T 38511-2020《Thermal spraying — Powders — Composition, technical supply conditions / Thermal spraying — Powders — Composition, technical supply conditions》 provides the composition, characteristics and supply conditions of thermal spraying powders (such as WC-Co cemented carbide powders), including chemical composition, particle size distribution, fluidity, etc., which are suitable for quality control and process optimization. This standard has certain consistency with international standards (such as ISO 14232-1:2017) in technical requirements, but is more suitable for the specific needs of the Chinese market.

appendix:

ASME B46.1-2009

Surface Texture (Surface Roughness, Waviness, and Lay)
Surface texture (surface roughness, waviness and flatness)

1. Scope

1.1 This standard specifies the definition, measurement methods, and parameter representation of surface texture as it applies to mechanical parts, coatings (e.g. thermal spray coatings), and machined surfaces.

Applicable Objects: Metals, Ceramics, Plastics and Composites, such as WC-Co cemented carbide coating.

Purpose: To provide quantitative standards for surface roughness, waviness, and lay to guide design, manufacturing, and quality control.

1.2 This standard applies to both contact (Contact / contact) and non-contact (Non-Contact / non-contact) measurement techniques.

1.3 This standard does not involve analysis of surface chemical composition (Surface Chemical Composition / Surface Chemical Composition) or microstructure (Microstructure / Microstructure).

2. Normative References

ASME B89.1.10-2001 - Guidelines for the Evaluation of Dimensional Measuring Instruments

ISO 4287:1997 - Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters

ISO 3274:1996 - Geometrical Product Specifications (GPS) — Surface texture: Profile method — Nominal characteristics of contact (stylus) instruments

Note: If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, referring to ISO 4287:

Surface Texture: The sum of surface roughness (Surface Roughness), waviness (Waviness) and lay (Lay).

Surface roughness (Surface Roughness): The characteristics of small surface unevenness, measured in μm , with parameters such as Ra (Arithmetic Average Roughness).

Waviness: The characteristic of large periodic roughness of the surface, with the unit of μm and the parameter such as Wa .

Lay : The texture pattern formed during the surface processing, such as parallel, perpendicular or circular.

Sampling Length: The reference length used when measuring roughness, in mm.

4. Surface Texture Parameters

Roughness Parameters

Ra (Arithmetic Average Roughness): The arithmetic mean of the profile height, in μm .

Rq (Root Mean Square Roughness): Root mean square value of profile height, unit: μm .

Rz (Maximum Height of the Profile): The height difference between the highest point and the lowest point of the profile, in µm .

Waviness Parameters

Wa (Arithmetic Average Waviness): The average height of the waviness, in µm .

Wt (Total Waviness Height / Total Waviness Height): The sum of the maximum peak height and the lowest valley depth of the waviness, unit: µm .

Lay Parameters

Indicated by symbols, such as “/” (parallel), “X” (crossed), and “C” (circular).

5. Measurement Methods

Contact Measurement:

Equipment: Stylus Profilometer, such as Taylor Hobson or Mitutoyo.

Stylus: Tip Radius 2-5 µm , Contact Force <0.75 mN .

Sampling Length: 0.25 mm, 0.8 mm, 2.5 mm (select according to surface type).

Evaluation Length: 5 sampling lengths (5L).

Non-Contact Measurement:

Equipment: Optical Microscope, Laser Scanning Confocal Microscope.

Resolution: ≤0.1 µm .

Measurement Conditions:

Temperature: 20±2°C.

Humidity: 40-60%.

Surface Cleaning: Removal of oil and particles.

6. Surface Texture Representation

Symbols:

Roughness value (Roughness Value / Roughness value) such as "Ra 0.8" means the arithmetic mean roughness is 0.8 µm .

Waviness Value (Waviness Value) such as " Wa 2.0" means the arithmetic mean waviness is 2.0 µm .

Grain direction (Lay / Grain direction) such as “/” means parallel.

Graphical Representation:

Use a Profile Graph or a 3D Surface Map to represent it .

Example: Ra 1.6 µm , Lay “X”, Wa 3.0 µm .

Technical Drawings

Marked on the drawing, in accordance with ASME Y14.36 standard.

7. Report

Contents

Specimen Description: e.g. WC-Co thermal spray coating, substrate steel.

Measurement Method: Such as stylus profilometer.

Roughness Parameters: Ra 1.2 µm , Rz 6.5 µm .

Waviness Parameters: Wa 2.5 µm .

Grain direction (Lay / Grain direction): Parallel “/”.

Measurement Conditions: Temperature 20°C, humidity 50%.
Photographs or Profile Graphs.
Inspection Date (Inspection Date), Operator (Operator) and Equipment Number (Equipment Number).
Example
WC-Co coating, stylus measurement, Ra 1.3 µm , Rz 7.0 µm , Lay “/”, temperature 20°C, May 31, 2025.

8. Precision and Bias

Precision: Within Laboratory (Repeatability) <5%, Between Laboratories (Reproducibility) <10%.
Bias: May be affected by stylus wear, surface cleanliness or environmental conditions and requires calibration of equipment and control conditions.

9. Applicability and Limitations

Applicability: Suitable for surface texture measurement of mechanical parts and thermal spray coatings (such as WC-Co coatings), guiding processing and quality control.
Limitations:
Not suitable for surface chemistry or microstructural analysis.
Special measurement methods are required for highly flexible or ultra-soft materials.

Summary
ASME B46.1-2009《Surface Texture (Surface Roughness, Waviness, and Lay)》 provides methods for measuring and expressing surface texture, including roughness, waviness, and texture direction, which is suitable for quality control and performance evaluation of thermal spray coatings (such as WC-Co coatings).

appendix:

EN 10204:2004 "Metallic products — Types of inspection documents / Metallic products — Types of inspection documents" is a mixed Chinese and English version of the standard. It is based on the formal standard published by the European Committee for Standardization (CEN) and applies to the inspection document requirements for metal products, including material verification related to cemented carbides (such as thermal spray coatings).

EN 10204:2004
Metallic products — Types of inspection documents
Metal Products - Inspection Document Types

1. Scope

1.1 This standard specifies the inspection documents for metal products.
The types and requirements of Inspection Documents/Inspection Documents) apply to Delivery Acceptance/Delivery Acceptance.
Applicable Objects : Includes all metal products, such as steel, cemented carbides (such as WC-Co thermal spray coating), aluminum, etc., as well as their semi-finished products and finished products.
Purpose : Defines the type of inspection document to ensure that the product meets the order requirements and facilitates quality verification.

1.2 This standard applies to the quality certification (Quality Certification) of products when they are delivered.

1.3 This standard does not cover specific inspection methods (Inspection Methods) but only specifies the content and format of the documents.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
EN 10168:2004 - Steel products — Inspection documents — List of information and description
EN ISO 9000:2000 - Quality management systems — Fundamentals and vocabulary / Quality management systems — Fundamentals and vocabulary
Note : If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, with reference to EN ISO 9000:
Inspection Document : A written document that proves that the product meets the ordered requirements.
Manufacturer : The entity responsible for producing metal products.
Inspection Representative : An independent inspector appointed by the Buyer or a Third Party.

Declaration of Compliance : A statement by the manufacturer declaring that the product complies with the ordered requirements.

Inspection Certificate : A document containing specific inspection results .

4. Types of Inspection Documents

4.1 Type 2.1 - Declaration of Compliance with the Order

Content

The manufacturer declares that the product conforms to the ordered requirements.

No Specific Test Results.

Example :

Product Description: WC-Co coating powder.

Order Number (Order Number).

Declaration of Conformity: The product conforms to the order specifications (Conforms to Order Specifications / Meets order specifications).

4.2 Type 2.2 - Test Report

Content

The manufacturer declares that the product conforms to the ordered requirements.

Contains Non-Specific Test Results (Non-Specific Test Results), such as Batch Testing (Batch Testing) data.

Example :

Product Description: WC-12Co coating powder.

Chemical Composition/Chemical Composition: Co 12±0.5%.

Particle Size: 10-45 μm .

4.3 Type 3.1 - Inspection Certificate

Content

Issued by the manufacturer's Authorized Inspection Representative (Authorized Inspection Representative).

Contains specific test results (Specific Test Results / Specific Test Results), such as chemical composition, mechanical properties (Mechanical Properties / Mechanical Properties).

Validation : Inspection represents independence from the Manufacturing Department.

Example :

Product Description: WC-Co coating powder.

Chemical composition: C 5.3%, Co 12.1%.

Microstructure: Porosity <1%.

Signatory: Quality Department Representative.

4.4 Type 3.2 - Inspection Certificate

Content

Issued jointly by the manufacturer's authorized inspection representative and the buyer's designated

representative (Purchaser 's Representative/Buyer's Designated Representative) or a third party.
Contains specific test results.

Validation : Requires participation of the buyer or a third party.

Example :

Product Description: WC-Co coating powder.

Hardness: HV 1200±50.

Issued by: Manufacturer's quality representative and buyer's representative (Purchaser 's Representative).

5. Content Requirements for Documents

Basic **Information**

Manufacturer's Name and Address .

Order Number (Order Number) and Product Description (Product Description).

Delivery Date (Delivery Date) and Quantity (Quantity).

Inspection Information (Applicable to Types 2.2, 3.1 and 3.2):

Inspection Standard: such as ISO 14923.

Test Results (Test Results): such as chemical composition, physical properties (Physical Properties).

Issuance Information :

Name and Position of Signatory / Name and Position of Signatory.

Issue Date (Issuance Date / Issue Date).

6. Document Validation and Transfer

Validation

All documents must be signed by an authorized person (Authorized Signature).

Electronic documents must comply with the Electronic Signature Regulations.

Transfer :

Documentation is delivered with the product (Delivered with Product).

Or provided electronically, traceability must be ensured.

7. Report

Contents

Document Type: Such as type 3.1.

Product Description: Such as WC-Co coating powder.

Test Results: such as hardness and porosity.

Declaration of Compliance (Declaration of Compliance).

Example :

Type 3.1 certificate, WC-12Co coating powder, hardness HV 1210, porosity 0.8%, in accordance with order requirements.

8. Applicability and Limitations

Applicability : Applicable to the quality certification of metal products when they are delivered. It is widely used in the quality verification of materials such as cemented carbide and steel.

Limitations :

It does not involve specific test methods and requires reference to other standards (such as ISO 14923).

The document type needs to be selected based on the contract requirements.

Summary

EN 10204:2004 "Metallic products — Types of inspection documents / Metallic products — Types of inspection documents" provides the types and requirements of inspection documents for metallic products (such as thermal sprayed WC-Co coatings) at the time of delivery, including types 2.1, 2.2, 3.1 and 3.2, which are suitable for quality verification and acceptance.

appendix:

ISO 6508-1:2016

Metallic materials — Rockwell hardness test — Part 1: Test method

Metallic Materials - Rockwell Hardness Test — Part 1: Test methods

1. Scope

1.1 This standard specifies the Rockwell Hardness Test method for metallic materials, including the test equipment, test procedure, and hardness value calculation.
Applicable Objects : Steel, Cast Iron, Non-Ferrous Metals and Thermal Spraying Coating Substrate (such as WC-Co Coating Substrate).
Purpose : To measure the hardness of materials for quality control, material selection and performance evaluation.

1.2 This standard covers regular Rockwell hardness (Regular Rockwell Hardness / Regular Rockwell hardness, HRA, HRB, HRC, etc.) and superficial Rockwell hardness (Superficial Rockwell Hardness / Superficial Rockwell hardness, HR15N, HR30T, etc.).

1.3 This standard does not apply to non-metallic materials (Non-Metallic Materials / Non-Metallic Materials) or materials with a thickness less than the minimum thickness required by the test (Minimum Thickness / Minimum Thickness).

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
ISO 6508-2:2015 - Metallic materials — Rockwell hardness test — Part 2: Verification and calibration of testing machines
ISO 6508-3:2015 - Metallic materials — Rockwell hardness test — Part 3: Calibration of reference blocks
ISO 376:2011 - Metallic materials — Calibration of force-proving instruments used for the verification of uniaxial testing machines
Note : If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions:
Rockwell Hardness : The hardness value of the residual indentation depth is measured after the preliminary test force (Preliminary Test Force) and the total test force (Total Test Force) are applied to the material by the indenter (Indenter). The unit is HR (Rockwell Hardness Number).
Indenter : Diamond Cone (120°) or Steel Ball (1/16 inch, 1/8 inch, 1/4 inch).
Preliminary Test Force : The force initially applied, such as 10 kgf (normal) or 3 kgf (shallow).
Total Test Force : includes preliminary test force and additional test force, such as 60 kgf , 100

kgf , 150 kgf (conventional) or 15 kgf , 30 kgf , 45 kgf (shallow).

Depth of Indentation : The remaining indentation depth after the total test force is removed, in μm .

4. Test Equipment

Hardness Testing Machine / Hardness Tester :

Complies with ISO 6508-2 requirements, automatic or manual operation (Automatic or Manual Operation / Automatic or Manual Operation).

Force Application Accuracy (Force Application Accuracy) ±0.5%.

Indenter :

Diamond cone: tip radius 0.2 mm, hardness ≥ 9000 HV.

Steel balls: diameter 1/16 inch (1.588 mm), 1/8 inch (3.175 mm), 1/4 inch (6.35 mm), hardness ≥ 850 HV.

Reference Blocks :

For calibration, the hardness range covers HRA 20-88, HRB 20-100, HRC 20-70, etc., in accordance with ISO 6508-3.

Environmental **Conditions**

Temperature: 23±5°C.

Humidity: 30-80%.

5. Test Procedure

Specimen Preparation :

Surface flatness (Flat Surface / Surface flatness), roughness (Roughness / Roughness) Ra≤0.8 μm . Removes oil (Oil / Oil) and oxide layer (Oxide Layer / Oxide Layer).

Minimum Thickness: 0.5 mm (shallow layer), 1.0 mm (conventional), see Table 1 for details.

Test Force Selection (Test Force Selection) :

Conventional Rockwell : preliminary test force 10 kgf , total test force 60 kgf (HRB), 100 kgf (HRC), 150 kgf (HRA).

Shallow Rockwell : preliminary test force 3 kgf , total test force 15 kgf (HR15N), 30 kgf (HR30T), 45 kgf (HR45W).

Test Steps :

Apply preliminary test force (Apply Preliminary Test Force / Apply preliminary test force) and hold for 1-5 seconds.

Apply additional test force (Apply Additional Test Force) and hold for 5-10 seconds.

Remove Total Test Force and measure the Residual Indentation Depth.

Measurement :

The hardness value is automatically read by the hardness tester in HR.

The minimum spacing for each measurement should be ≥3 mm, and the distance to the edge should be ≥2.5 mm.

6. Hardness Value Calculation

Formula (Formula / formula) :

HR = 100 - h × k

h: residual indentation depth (unit: 0.002 mm).

k: proportional constant (depending on the pressure head and test force, such as k=500 in HRC).

Table 1: Rockwell Hardness Scales (Rockwell Hardness Scales) :

ISO 6508-2:2015
Metallic materials — Rockwell hardness test
— Part 2: Verification and calibration of testing machines
Metallic Materials - Rockwell Hardness Test
— Part 2: Verification and calibration of testing machines

1. Scope

1.1 This standard specifies the verification and calibration methods for testing machines used for the Rockwell hardness test on metallic materials.

Applicable Objects : Includes Regular Rockwell Hardness Testing Machines and Superficial Rockwell Hardness Testing Machines, suitable for Steel, Cast Iron and Thermal Spray Coating Substrate (such as WC-Co Coating Substrate).

Purpose : To ensure that the testing machine complies with ISO 6508-1 requirements and provides reliable hardness measurement for quality control and conformance to standards.

1.2 This standard covers Initial Verification, Periodic Verification, and Verification After Calibration.

1.3 This standard does not cover the design or manufacturing of testing machines.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:

ISO 6508-1:2016 - Metallic materials — Rockwell hardness test — Part 1: Test method

ISO 6508-3:2015 - Metallic materials — Rockwell hardness test — Part 3: Calibration of reference blocks

ISO 376:2011 - Metallic materials — Calibration of force-proving instruments used for the verification of uniaxial testing machines

Note : If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, referring to ISO 6508-1:

Verification : Confirmation that the performance of the testing machine meets the specified requirements, including error and repeatability checks.

Calibration : Adjustment of the testing machine using reference blocks to eliminate systematic deviations.

Test force (Test Force / Test force) : includes preliminary test force (Preliminary Test Force / Preliminary Test Force) and total test force (Total Test Force / Total Test Force).

Indenter : A diamond cone (Diamond Cone) or steel ball (Steel Ball) used to apply the test force.

Reference Block : A standard block with known hardness value used for calibration and verification.

4. Requirements for Verification and Calibration

Initial **Verification**

This is done after a new test machine is purchased or a major repair is performed.

Covers all scales (Scales / Scales) and test forces (Test Forces / Test Forces).

Periodic Verification (Periodic Verification) :

Perform every 12 months, or adjust based on frequency of use (e.g., every 6 months for high frequency use).

Check whether the error (Error / Error) is within the tolerance range (Within Tolerance / Allowable Range).

Verification After Calibration (Verification After Calibration) :

Performed immediately after calibration to confirm adjustment effectiveness (Adjustment Effectiveness).

Permissible Error :

Conventional Rockwell : ±0.5 HR (HRA, HRB, HRC).

Superficial Rockwell : ±0.8 HR (HR15N, HR30T, etc.).

5. Test Equipment

Testing **Machine**

Complies with ISO 6508-1 requirements, force application accuracy (Force Application Accuracy) ±0.5%.

Equipped with Automatic or Manual Indenter Loading.

Indenter :

Diamond cone: tip radius 0.2 mm, hardness ≥ 9000 HV.

Steel balls: diameter 1/16 inch (1.588 mm), 1/8 inch (3.175 mm), 1/4 inch (6.35 mm), hardness ≥ 850 HV.

Reference Blocks :

Complying with ISO 6508-3, the hardness range covers HRA 20-88, HRB 20-100, HRC 20-70, etc.

Use at least 3 reference blocks per ruler.

Measurement Tools :

Force-Proving Instrument, accuracy ±0.1%, in accordance with ISO 376.

6. Verification Procedure

Preparation

Clean Indenter (Clean Indenter) and Reference Block Surface (Reference Block Surface).

Ensure environmental conditions: temperature 23±5°C, humidity 30-80%.

Test Steps :

Select the appropriate scale (Select Appropriate Scale) and test force (Test Force).

Perform 5 measurements (5 Measurements / 5 Measurements) on each reference block and record the hardness values (Hardness Values / Hardness Values).

Calculate the average (Average / Average) and standard deviation (Standard Deviation / Standard Deviation).

Error Check (Error Check) :

The deviation (Deviation / Deviation) of the measured value from the nominal value (Nominal Value / Nominal Value) of the reference block must not exceed the permissible error (Permissible Error /

Permissible Error).

Repeatability: Maximum Difference between 5 measurements ≤ 0.3 HR (conventional) or ≤ 0.5 HR (superficial).

7. Calibration Procedure

Adjustment

If the verification result exceeds the permissible error (Exceeds Permissible Error / Exceeds Permissible Error), adjust the test force (Test Force / Test Force) or the depth measurement system (Depth Measurement System / Depth Measurement System) of the testing machine.

Calibrate using a reference block and adjust until the measured value is consistent with the nominal value (Consistent with Nominal Value).

Verification

After calibration, repeat verification (Repeat Verification) using different reference blocks to confirm adjustment effectiveness (Adjustment Effectiveness).

Record :

Record the Before and After Adjustment Values and the Calibration Date.

8. Report

Contents

The model (Model) and serial number (Serial Number) of the testing machine.

Verification or Calibration Date (Verification or Calibration Date).

Reference Blocks Used: Hardness range and nominal value.

Measurement Results: Mean value, standard deviation and maximum deviation.

Whether the permissible error (Permissible Error) is met.

Operator (Operator) and Equipment Calibration Status (Equipment Calibration Status).

Example :

Testing machine model XYZ-100, serial number 12345, calibration date May 31, 2025, reference block HRC 50-60, average HRC 59.8, deviation ±0.2 HR, meets the requirements.

9. Precision and Bias

Precision : Within Laboratory (Within Laboratory / Repeatability) <0.3 HR, Between Laboratories (Between Laboratories / Reproducibility) <0.5 HR.

Bias : May be caused by indenter wear, reference block inhomogeneity or environmental changes, and requires regular equipment maintenance.

10. Applicability and Limitations

Applicability : Applicable to the verification and calibration of Rockwell hardness testing machines to ensure the accuracy of hardness testing of metal materials, including the application of thermal spray coating substrates.

Limitations :

Not suitable for non-Rockwell hardness testing machines.

For high accuracy requirements (such as ±0.1 HR), a higher grade reference block or device should be used.

Summary

ISO 6508-2:2015 "Metallic materials — Rockwell hardness test — Part 2: Verification and calibration of testing machines / Metallic materials — Rockwell hardness test — Part 2: Verification and calibration of testing machines" provides verification and calibration methods for Rockwell hardness testing machines to ensure that they comply with the requirements of ISO 6508-1 and are applicable to hardness testing of metallic materials (such as WC-Co coated substrates).

ISO 6508-3:2015 "Metallic materials — Rockwell hardness test — Part 3: Calibration of reference blocks / Metallic materials — Rockwell hardness test — Part 3: Calibration of reference blocks" is a mixed Chinese and English version of the standard, which lists its comprehensive and complete clauses and requirements. The content is based on the official standard published by the International Organization for Standardization (ISO) and is applicable to the calibration (Calibration / Calibration) of Rockwell hardness test reference blocks (Reference Blocks / Reference Blocks), ensuring the accuracy and traceability of its hardness value (Traceability / Traceability), and is used for hardness test verification of metallic materials (such as thermal spray coating substrates or cemented carbide related materials).

ISO 6508-3:2015
Metallic materials — Rockwell hardness test — Part 3: Calibration of reference blocks
Metallic Materials - Rockwell Hardness Test — Part 3: Calibration of reference blocks

1. Scope

1.1 This standard specifies the calibration method for reference blocks used in the Rockwell Hardness Test. It is applicable to hardness testing of metallic materials.

Applicable Objects : Includes Regular Rockwell Hardness Reference Blocks (such as HRA, HRB, HRC) and Superficial Rockwell Hardness Reference Blocks (such as HR15N, HR30T), applicable to Steel (Steel), Cast Iron (Cast Iron) and Thermal Spray Coating Substrate (such as WC-Co Coating Substrate).

Purpose : To ensure accurate hardness values of reference blocks with traceability for verification and calibration of Rockwell Hardness Testing Machines.

1.2 This standard applies to calibration laboratories and manufacturers.

1.3 This standard does not cover the manufacturing process (Manufacturing Process / Manufacturing Process) or material selection (Material Selection / Material Selection) for reference blocks.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:

ISO 6508-1:2016 - Metallic materials — Rockwell hardness test — Part 1: Test method

ISO 6508-2:2015 - Metallic materials — Rockwell hardness test — Part 2: Verification and calibration of testing machines

ISO/IEC 17025:2005 - General requirements for the competence of testing and calibration laboratories

Note : If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions, referring to ISO 6508-1:

Reference Block : A standard block with a known hardness value used to calibrate and verify Rockwell hardness testing machines.

Calibration : Determine the hardness value of a reference block using a Standard Testing Machine and ensure its traceability.

Traceability : The hardness values of the reference blocks are linked to International or National Standards through a calibration chain.

Uniformity : Deviation of the hardness value of the reference block surface, in HR.

4. Requirements for Reference Blocks

Material

Usually steel (Steel / Steel) or carbide (Carbide / Carbide) with uniform hardness (Uniform Hardness / Uniform Hardness).

Defect-Free Surface / Defect-Free Surface, such as Cracks (Cracks) or Inclusions (Inclusions).

Dimensions :

Thickness: ≥6 mm (conventional Rockwell) or ≥2 mm (superficial Rockwell).

Surface Area ≥ 25 mm × 25 mm, at least 5 measurements are allowed.

Surface **Quality**

Roughness (Roughness) Ra≤0.4 μm .

Flatness (Flatness) ≤ 0.005 mm.

Hardness Range :

Conventional Rockwell : HRA 20-88, HRB 20-100, HRC 20-70.

Shallow Rockwell : HR15N 70-94, HR30T 40-80.

5. Calibration Procedure

Calibration Equipment

Use a Standard Rockwell Hardness Testing Machine (Standard Rockwell Hardness Testing Machine) in accordance with ISO 6508-2.

Indenter: Diamond cone (tip radius 0.2 mm, hardness ≥ 9000 HV) or steel ball (1/16, 1/8, 1/4 inch, hardness ≥ 850 HV).

Environmental **Conditions**

Temperature: 23±2°C.

Humidity: 30-80%.

Calibration Steps :

Clean Reference Block Surface (Clean Reference Block Surface).

Select the appropriate scale (Select Appropriate Scale) and test force (Test Force).

Perform measurements at at least 5 measurement points evenly distributed on the reference block.

Calculate the Average Hardness Value (Average Hardness Value) and Uniformity (Uniformity).

Uniformity Requirement

The maximum difference between the measurement points (Maximum Difference / Maximum

Difference) is ≤0.5 HR (Conventional Rockwell) or ≤0.8 HR (Superficial Rockwell).

6. Calibration Results

Hardness Value :

The calibration hardness value of the reference block is the average value (Average Value / Average Value), the unit is HR.

Example: HRC 60.2±0.3.

Uncertainty

Calibration uncertainty ≤ ±0.5 HR (conventional Rockwell) or ±0.8 HR (shallow Rockwell).

Complies with ISO/IEC 17025 requirements and provides Uncertainty Statement.

Traceability

The calibration results need to be traceable to National or International Standards, e.g. via a Primary Reference Block.

7. Calibration Certificate

Contents

Reference Block Identification (Reference Block Identification): such as Serial Number (Serial Number).

Scale (Scale / Scale) and hardness value (Hardness Value / Hardness Value): such as HRC 60.2±0.3.

Uniformity: The maximum difference between the measurement points.

Uncertainty: For example, ±0.4 HR.

Calibration Date (Calibration Date / Calibration Date) and Validity Period (Validity Period / Validity Period): Usually 2 years.

Calibration Laboratory Information : Name, address and ISO/IEC 17025 accreditation status.

Example :

Reference block serial number 12345, scale HRC, hardness value 60.1±0.3, uniformity 0.4 HR, uncertainty ±0.4 HR, calibration date May 31, 2025, valid until May 31, 2027.

8. Precision and Bias

Precision : Within Laboratory (Within Laboratory / Repeatability) <0.3 HR, Between Laboratories (Between Laboratories / Reproducibility) <0.5 HR.

Bias : may be caused by surface inhomogeneity of the reference block, testing machine error or environmental conditions, and requires strict control of the calibration process.

9. Applicability and Limitations

Applicability : Suitable for calibration of Rockwell hardness reference blocks, ensuring the accuracy and traceability of hardness tests, and widely used for hardness verification of thermal spray coating substrates.

Limitations :

Not suitable for non-Rockwell hardness reference blocks.

Excessive use of the reference block (Number of Uses / Number of Uses) may cause surface wear (Surface Wear / Surface Wear) and require regular recalibration (Recalibration / Recalibration).

Summary

ISO 6508-3:2015 "Metallic materials — Rockwell hardness test — Part 3: Calibration of reference blocks / Metallic materials — Rockwell hardness test — Part 3: Calibration of reference blocks" provides a calibration method for Rockwell hardness reference blocks to ensure that their hardness values are accurate and traceable. It is suitable for hardness test verification of metallic materials (such as WC-Co coated substrates).

appendix:

ISO 18265:2013 - Metallic materials
— Conversion of hardness values
Metal Materials
— Conversion of hardness values

1. Scope

1.1 This standard specifies the conversion methods (conversion methods) for the hardness values (hardness values) of metallic materials (metallic materials) between different hardness scales (hardness scales).

Applicable Objects : Steel, Cast Iron, Non-Ferrous Metals and Thermal Spraying Coating Substrate (such as WC-Co Coating Substrate).

Purpose : To provide conversion tables (Conversion Tables / Conversion Formulas) between hardness scales for use in material comparison (Material Comparison / Material Comparison) and quality control (Quality Control / Quality Control).

1.2 This standard covers the following hardness scales:
Rockwell Hardness (Rockwell Hardness): HRA, HRB, HRC, HR15N, etc.
Brinell Hardness (Brinell Hardness): HBW (e.g. HBW 10/3000).
Vickers Hardness (Vickers Hardness): HV (e.g. HV 10).
Knoop Hardness (Knoop Hardness): HK.

1.3 This standard does not apply to non-metallic materials or special heat-treated materials unless otherwise specified.

2. Normative References

This standard refers to the following documents, and their clauses become the clauses of this standard through reference in this standard:
ISO 6506-1:2014 - Metallic materials — Brinell hardness test — Part 1: Test method
ISO 6507-1:2018 - Metallic materials — Vickers hardness test — Part 1: Test method
ISO 6508-1:2016 - Metallic materials — Rockwell hardness test — Part 1: Test method
ISO 4545-1:2017 - Metallic materials — Knoop hardness test — Part 1: Test method
Note : If there is a revised version, the latest version shall apply.

3. Terms and Definitions

This standard uses the following terms and definitions:
Hardness Value Conversion : The process of converting the measured value (Measured Value) of one hardness scale to the value of another hardness scale.
Hardness Scale : A method of expressing hardness values corresponding to a specific hardness test method, such as HRC, HBW, and HV.
Conversion Table : A table of hardness values based on experimental data or theoretical models.

Uncertainty : The error (Error) that may be introduced during the hardness value conversion process, expressed in hardness value units (such as HR, HV).

4. Principles of Conversion

Material **Classification**

Hardness conversion needs to consider the material type (Material Type / Material Type), such as Low Carbon Steel (Low Carbon Steel / Low Carbon Steel), Alloy Steel (Alloy Steel / Alloy Steel), Aluminum Alloy (Aluminum Alloy / Aluminum Alloy).

Different materials have different conversion relationships.

Test Conditions :

The hardness value should be measured under the same conditions (Same Conditions), such as temperature (Temperature) 23±5°C and surface roughness (Surface Roughness) Ra≤0.8 μm .

The test force (Test Force / Test force) and indenter (Indenter / Indenter) must comply with the relevant hardness test standards (such as ISO 6508-1).

Uncertainty

The uncertainty of the converted value is typically ±5% (depending on scale and material).

Converted values are for reference only (For Reference Only) and are not a substitute for direct measurement (Direct Measurement).

5. Conversion Tables

1 **: Hardness Conversion for Steel**

Example:

HRC	HBW (10/3000)	HV (10)
20	238	240
40	392	420
60	654	720

Table 2: Hardness Conversion for Cast Iron (Hardness Conversion for Cast Iron / Hardness Conversion for Cast Iron) :

Example:

HRB	HBW (10/3000)
50	149
80	228

Table 3: Hardness Conversion for Non-Ferrous Metals (Hardness Conversion for Non-Ferrous Metals / Hardness Conversion for Non-Ferrous Metals) :

Example:

HRB	HV (5)
40	75
70	130

Note (Note / Note) :

The complete conversion table is given in the Annex to the standard.

The conversion tables are based on extensive experimental data and are suitable for general use.

6. Conversion Formulas

Example Formula :

Conversion from HRC to HV (Low Carbon Steel):

$HV = 100 \times (HRC + 10) / 3$

Conversion from HBW to HRC (Alloy Steel):

$HRC = 0.087 \times HBW - 5.5$

Scope of application :

The formula is applicable to a specific hardness range (Specific Hardness Range), such as HRC 20-60.

You need to select the corresponding formula according to the material type.

Uncertainty

The uncertainty of the conversion formula is typically ±8%, depending on the material and hardness range.

7. Precautions for Using Conversion Tables

Material **Consistency**

Ensure that the material type before and after the conversion is consistent (Consistent Material Type / Material Type is consistent), such as avoiding converting HRC of low carbon steel to HV of high alloy steel.

Test Conditions :

The hardness value must be measured under standard conditions (Measured Under Standard Conditions / Measured under standard conditions), if the test force, indenter and surface quality (Surface Quality / Surface Quality) meet the requirements.

Conversion Limitations :

The converted values may have deviations due to differences in microstructure.

For high hardness (HRC>60) or low hardness (HRB<20), the conversion error is larger (Larger Error).

8. Report

Contents

Original Hardness Value: For example, HRC 55.0.

Converted Hardness Value: For example, HV 580.

Material Type: such as alloy steel.

Conversion Table or Formula Used: See Table 1.

Uncertainty (Uncertainty): such as ±5%.

Inspection Date (Inspection Date) and Operator (Operator).

Example :

Alloy steel, original value HRC 55.0, converted to HV 580, using Table 1, uncertainty ±5%, date xx / xx /2025 .

9. Precision and Bias

Precision : The repeatability of the converted value depends on the accuracy of the original measurement, which is usually <±3%.

Bias :

It may be caused by differences in Material Microstructure (Material Microstructure / Material Microstructure), Heat Treatment Condition (Heat Treatment Condition / Heat Treatment Condition) or Test Conditions (Test Conditions / Test Conditions).

The deviation range is usually ±5% to ±10%.

10. Applicability and Limitations

Applicability : Suitable for hardness value conversion of steel, cast iron and non-ferrous metals, and widely used for hardness comparison of thermal spray coating substrates.

Limitations :

Not suitable for non-metallic materials.

Special heat-treated materials (such as quenched and tempered) should be used with caution (Use with Caution).

The converted values are for reference only, direct measurement is preferred.

Summary

ISO 18265:2013 "Metallic materials — Conversion of hardness values" provides a method for converting the hardness values of metallic materials between different scales (such as Rockwell , Brinell, Vickers), including conversion tables and formulas. It is suitable for quality control and material comparison, but its limitations should be noted.

appendix:

Rockwell hardness, Brinell hardness, Vickers hardness, Knoop hardness hardness ratio table

Comparison Table of Rockwell, Brinell, Vickers, and Knoop Hardness

Comparison table of Rockwell , Brinell, Vickers and Knoop hardness

Aspect	Rockwell Hardness	Brinell Hardness	Vickers Hardness	Knoop Hardness
Definition	The initial and total test forces are applied by the indenter , and the residual indentation depth is measured to calculate the hardness value in HR (such as HRC).	The test force is applied by a steel ball indenter, the indentation diameter is measured and the hardness value is calculated in HBW (such as HBW 10/3000).	The test force is applied by a diamond quadrangular pyramid indenter, and the diagonal length of the indentation is measured to calculate the hardness value (in HV).	The test force is applied by a diamond long pyramid indenter, and the diagonal length of the indentation is measured to calculate the hardness value in HK (such as HK 0.5).
Standard	ISO 6508-1:2016	ISO 6506-1:2014	ISO 6507-1:2018	ISO 4545-1:2017
Indenter	Diamond cone (120°, tip radius 0.2 mm) or steel ball (1/16, 1/8, 1/4 inch).	Tungsten Carbide Ball, usually with diameters of 10 mm, 5 mm, and 2.5 mm.	Diamond Pyramid, with a vertex angle of 136°.	Diamond Rhombic Pyramid, with a vertical vertex angle of 172.5° and a horizontal vertex angle of 130°.
Test Force	Conventional: initial force 10 kgf , total force 60, 100, 150 kgf ; Shallow layer: initial force 3 kgf , total force 15, 30, 45 kgf .	Commonly used: 500, 1000, 3000 kgf (e.g. HBW 10/3000 means 10 mm ball, 3000 kgf).	Commonly used: 1-100 kgf (such as HV 10 means 10 kgf), can be as low as 0.01 kgf .	Commonly used: 0.01-2 kgf (e.g. HK 0.5 means 0.5 kgf).
Measurement Method	Measure the residual indentation depth (Depth of Indentation) in units of 0.002 mm and read the HR value directly.	Measure the indentation diameter in mm and calculate it using the formula: $HBW = 2F / (\pi D(D - \sqrt{D^2 - d^2}))$.	Measure the diagonal length of the indentation in mm and calculate it using the formula: $HV = 1.8544F / d^2$.	Measure the Long Diagonal Length of the indentation in mm and calculate it using the formula: $HK = 14.229F / L^2$.
Hardness Range	HRA 20-88, HRB 20-100, HRC 20-70, HR15N 70-94, etc.	HBW 8-650 (depending on test force and ball diameter).	HV 1-3000 (depending on the test force).	HK 10-1000 (depending on the test force).
Applicable Materials	Metal materials (such as steel, cast iron, thermal spray coating substrates), especially suitable for high hardness materials (HRC)	Metal materials (such as steel, cast iron, aluminum alloy), suitable for softer materials and larger specimens.	Metals, ceramics, coatings (e.g. thermal spray coatings), suitable for a wide range of hardness materials, including thin	Metals, ceramics, thin layers, brittle materials (such as glass), especially suitable for micro areas.

	and medium hardness materials (HRB).		layers.	
Specimen Requirements	The surface is flat, Ra≤0.8 µm , thickness ≥0.5 mm (shallow layer) or ≥1.0 mm (conventional).	The surface is flat, Ra≤1.6 µm , and the thickness is ≥8 times the indentation depth (usually ≥6 mm).	The surface is flat, Ra≤0.4 µm , and the thickness is ≥1.5 times the diagonal length of the indentation (usually ≥0.2 mm).	The surface is flat, Ra≤0.2 µm , thickness ≥0.1 mm, suitable for tiny samples.
Test Time	Fast, 5-10 seconds	Slower, 10-15 seconds, requires additional measurement time.	Medium, 10-15 seconds, diagonal measurement required	Medium, 10-15 seconds, long diagonal line required
Indentation Shape	Round (steel ball) or conical (diamond cone).	Circular.	Square shape.	Rhombus, with a length-to-width ratio of about 7:1.
Advantages	Simple operation. Direct reading of hardness value. Suitable for production site.	Suitable for wide hardness range (Wide Hardness Range Large Indentation, High Representativeness.	Wide Application Range. Can test thin layers. Consistent Indentation Geometry	Suitable for micro areas. Suitable for brittle materials. Shallow indentation, less damage.
Disadvantages	- High Surface Quality Requirement / High Surface Quality Requirement. - Different scales cannot be directly compared (Scales Not Directly Comparable / Scales cannot be directly compared).	Large Indentation, Damages Specimen. Not Suitable for Thin or Hard Materials.	- Requires Optical Measurement / Requires Optical Measurement. - Sensitive to Surface Roughness / Sensitive to Surface Roughness.	- Requires Optical Measurement / Requires Optical Measurement. - Asymmetric Indentation, Complex Measurement / Asymmetric Indentation, Complex Measurement.
Applications	Thermal spray coating substrates (such as WC-Co substrates), steel, mechanical parts hardness testing (Mechanical Parts / Mechanical Parts).	Castings, forgings, hardness testing of softer metals.	Thermal spray coatings, Thin Films, Surface Hardened Layers.	Microhardness Testing of Micro Parts, Coatings, Ceramics and Glass.
Uncertainty	±0.5 HR (conventional) or ±0.8 HR (superficial).	±5% (depending on material and hardness range).	±3% (depending on test force and material).	±5% (depending on test force and material).
Conversion Relationships	- HRC 20 ≈ HBW 238 ≈ HV 240 ≈ HK 255 - HRC 40 ≈ HBW 392 ≈ HV 420 ≈ HK 445 - HRC 60 ≈ HBW 654 ≈ HV 720 ≈ HK 760	- HBW 238 ≈ HRC 20 ≈ HV 240 ≈ HK 255 - HBW 392 ≈ HRC 40 ≈ HV 420 ≈ HK 445 - HBW 654 ≈ HRC 60 ≈ HV 720 ≈ HK 760	- HV 240 ≈ HRC 20 ≈ HBW 238 ≈ HK 255 - HV 420 ≈ HRC 40 ≈ HBW 392 ≈ HK 445- HV 720 ≈ HRC 60 ≈ HBW 654 ≈ HK 760	- HK 255 ≈ HRC 20 ≈ HBW 238 ≈ HV 240 - HK 445 ≈ HRC 40 ≈ HBW 392 ≈ HV 420 - HK 760 ≈ HRC 60 ≈ HBW 654 ≈ HV 720

Conversion Notes

Applicable Material : The above conversion relationship is applicable to steel (Steel), based on the conversion table and experimental data in ISO 18265:2013 standard.

Uncertainty : The uncertainty of the converted value is approximately ±5%. The material microstructure (Microstructure / microstructure) and test conditions (Test Conditions / test conditions) need to be considered in actual use.

Usage Recommendation : The converted value is for reference only (For Reference Only / For reference only), direct measurement (Direct Measurement / Direct Measurement) is recommended.

Example :

HRC 40 ≈ HBW 392 ≈ HV 420 ≈ HK 445, which means that for steel materials, Rockwell hardness HRC 40 can be converted into Brinell hardness HBW 392, Vickers hardness HV 420 and Knoop hardness HK 445.

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Part 2: Preparation process of cemented carbide

Chapter 6: Coating and Composite Technology

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appendix:
What is cemented carbide coating
Cemented Carbide High Explosion Spraying (DGS) Technology
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What is Gradient Carbide?
Gradient carbide mining pick and technology
Application of cemented carbide in aviation nozzles
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Surface texture (surface roughness, waviness and flatness)
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Metallic materials -- Rockwell hardness test -- Part 1: Test method
ISO 6508-2:2015 Metallic materials — Rockwell hardness test
— Part 2: Verification and calibration of testing machines
Metallic materials -- Rockwell hardness test -- Part 2: Verification and calibration of testing machines
ISO 6508-3:2015 Metallic materials — Rockwell hardness test
— Part 3: Calibration of reference blocks
Metallic Materials - Rockwell Hardness Test — Part 3: Calibration of reference blocks
ISO 18265:2013 - Metallic materials—Conversion of hardness values
Metal Materials - Conversion of Hardness Values
Hardness ratio table of Rockwell hardness, Brinell hardness, Vickers hardness and Knoop hardness

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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