Tungsten Cemented Carbide

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

中钨智造科技有限公司

CTIA GROUP LTD

CTIA GROUP LTD

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

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INTRODUCTION TO CTIA GROUP

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

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

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

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

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30 Years of Cemented Carbide Customization Experts

Core Advantages

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

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

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

Serving Customers

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

Service Commitment

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

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Chapter 16: Sustainability and Green Manufacturing

Sustainability and green manufacturing of cemented carbide focus on efficient resource utilization and minimized environmental impact. Through recycling and reuse (recovery rates >80%±5%), green processes (energy consumption reduction >20%±3%), and waste reduction (CO_2 emissions reduction >30%±5%), these efforts aim to recycle scarce resources such as tungsten (reserves <0.1%±0.01% of the Earth's crust) and cobalt (price fluctuation >50%±10%), while maintaining performance comparable to traditional processes (hardness HV 1600-2000±30, wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m). This chapter examines the recycling and reuse of cemented carbide, systematically analyzing its resource value, environmental benefits, and technical challenges, providing a theoretical and practical foundation for green manufacturing.

16.1 Recovery and reuse of cemented carbide

Cemented carbide recycling and reuse achieves efficient resource recycling through a variety of advanced processes, primarily chemical (acid and alkaline leaching, with recovery rates >85% ± 5%), physical (crushing and sorting, with purity >99% ± 0.5%), and metallurgical (smelting and reduction, with impurities <0.01% ± 0.001%). These methods effectively recover key elements such as tungsten and cobalt from cemented carbide, significantly reducing reliance on primary minerals (mining reductions >50% ± 5%) and environmental pollution (waste emissions reduced >40% ± 5%). These recycling processes are applicable not only to single waste materials such as used cutting tools and worn molds, but also to complex, multi-source waste materials (such as aviation

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components and automotive parts). By optimizing process parameters and equipment design, comprehensive recycling is achieved, from microstructure to macroscopic properties. This section examines the significance and challenges of cemented carbide recycling, providing an in-depth analysis combining resource value, environmental benefits, and technical challenges. The latest research findings and industrial practice data are introduced to ensure a professional and forward-looking discussion.

16.1.1 Significance and Challenges of Cemented Carbide Recycling

Cemented carbide recycling has far-reaching significance in terms of resource protection, environmental sustainability and economic benefits, while also facing complex process and technical challenges. The significance is mainly reflected in the following three aspects:

Cemented carbide recycling can alleviate the shortage of rare resources.
Tungsten reserves in the Earth's crust are extremely limited (<0.1% ± 0.01%), with proven global reserves estimated at 3.1 million tons ± 50,000 tons, primarily distributed in China (approximately 1.8 million tons ± 50,000 tons, accounting for 60% ± 5% of global reserves), Russia (approximately 500,000 tons ± 20,000 tons), and Canada (approximately 300,000 tons ± 10,000 tons). Tungsten's scarcity makes it a strategic metal, subject to international trade restrictions, mining depths (>500 m ± 50 m), and environmental regulations, resulting in high primary mining costs (>30 USD/kg ± 5 USD/kg). Cobalt reserves are even smaller (<0.01% ± 0.001%), with global reserves estimated at approximately 7 million tons ± 50,000 tons, of which the Democratic Republic of the Congo accounts for 60% ± 5%. Due to geopolitical risks (such as civil unrest and export bans) and supply chain disruptions, prices fluctuate significantly (over 50% fluctuations in the past five years, reaching as high as $80,000 ± 5,000 per ton). By recycling scrap (such as scrap tools, worn dies, and expired coatings), cemented carbide recycling can supplement global tungsten demand by 10% ± 2% (approximately 30,000 tons ± 500 tons) and cobalt demand by 8% ± 1% (approximately 12,000 tons ± 200 tons) annually, effectively alleviating resource shortages, particularly in the new energy battery (electric vehicle demand is growing by 20% ± 2% annually), aerospace (cobalt-based alloy demand is growing by 15% ± 2% annually), and cutting tools (tungsten demand is growing by 10% ± 1% annually).

Compared to primary mining, the recycling process significantly reduces greenhouse gas emissions (CO_2 **reduction > 30**
% ± 5%). This is because it avoids high-carbon processes such as ore excavation (energy consumption >2000 MJ/t ± 200 MJ/t, CO_2 emissions of approximately 20-30 t/t ± 2 t/t), transportation (fuel consumption >100 L/t ± 10 L/t, emissions of approximately 0.3 t/t ± 0.03 t/t), and smelting (blast furnace energy consumption >1500 kWh/t ± 100 kWh/t, emissions of approximately 1-2 t/t ± 0.1 t/t). For example, recycling 1000 tons of scrap cemented carbide can reduce CO_2 emissions by approximately 25,000 t ± 2,500 t, equivalent to the annual emissions of 5,000 gasoline-powered vehicles. Recycling also reduces land destruction caused by mining (reducing mining area by >1000 km^2) ± 100 km^2 (approximately 0.1% of global arable land), water

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pollution (e.g., heavy metal leaching reduced by >60% ± 5%, tungsten concentrations reduced from >500 ppm to <50 ppm ± 5 ppm), and tailings accumulation (reduced by >500,000 tons ± 50,000 tons). Through wastewater treatment (acid-base neutralization pH 7 ± 0.2, membrane filtration pore size 0.01 μm ± 0.001 μm, recovery rate >90% ± 2%) and residual waste resource utilization (incineration calorific value >10 MJ/kg ± 1 MJ/kg), the recycling industry further reduces its environmental impact, aligning with international carbon neutrality goals (such as the EU Green Deal) and circular economy policies.

The economic benefits

of cemented carbide recycling are typically lower than primary refining costs (<50% ± 10%). For example, primary tungsten refining costs are approximately $30-40 ± $5/kg (including ore mining at $15-20/kg, smelting at $10-15/kg, and transportation at $5/kg), while recycling costs can be reduced to $15-20 ± $2/kg (crushing and sorting at $5-7/kg, chemical treatment at $8-10/kg, and purification at $2-3/kg). The economic benefits of recycling can be further improved through large-scale production (annual processing capacity >10,000 ± 1,000 t) and process optimization (e.g., reducing energy consumption by 10% ± 1%, saving 50 kWh/t ± 5 kWh/t). In addition, recycled materials can be directly used for remanufacturing (e.g., extending cutting tool life by 20% ± 2% and improving wear resistance by 15% ± 2%), reducing raw material procurement expenses (savings > 20% ± 2%), and enhancing corporate competitiveness, especially in major cemented carbide consuming markets such as China (annual demand of 100,000 tons ± 10,000 tons), Germany (annual demand of 50,000 tons ± 5,000 tons), and the United States (annual demand of 40,000 tons ± 4,000 tons).

However, the cemented carbide recycling process also faces the following challenges:

Challenges of cemented carbide recycling - composition complexity

Cemented carbide is usually composed of tungsten carbide (WC, >85% ± 1%) and cobalt (Co, 6%-15% ± 1%), and contains trace additives (such as VC 0.5%-1% ± 0.1%, TaC 0.3%-0.8% ± 0.1%, TiC 0.2%-0.5% ± 0.1%). The different ratios of these additives in different products make recycling and separation more difficult. For example, aerospace-grade cemented carbide may contain TaC 0.5% ± 0.05% to improve high-temperature performance (temperature resistance > 1200°C ± 20°C), while general-purpose cutting tools may contain VC 0.8% ± 0.1% to inhibit grain growth (grain size < 0.5 μm ± 0.05 μm). Targeted adjustments are required for the acid leaching concentration (HNO_3 25-30 mol/L ± 0.1 mol/L) or electrolysis parameters (current density 50-200 A/m²). ± 10 A/m²) .

Challenges of cemented carbide recycling - impurity control

. Impurities such as iron (Fe, >50% ± 5% from equipment wear, such as ball mill balls), nickel (Ni, <0.005% ± 0.0005% from the oxide layer on the surface of scrap), copper (Cu, <0.002% ± 0.0002% from electrolysis by-products), and silicon (Si, <0.001% ± 0.0001% from sorting equipment) may be introduced during the recycling process. If the content exceeds <0.01% ± 0.001%, the performance of the recycled material will be degraded (e.g., hardness <2200 HV ± 50 HV, wear rate >0.05 mm³ / N · m ± 0.005 mm³ / N · m, fracture toughness K_{1c} <10 MPa·m$^{1/2}$ ± 0.5 MPa·m¹

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/ ²) . Impurity sources also include surface oxidation of waste materials (O content >0.2% ± 0.05%, affecting sintering density) and secondary contamination (particle surface adsorption >0.1% ± 0.01%), requiring multi-stage purification to ensure product quality.

The recycling process

consumes high amounts of energy (> 500 kWh/t ± 50 kWh/t), primarily in pickling (heating energy >200 kWh/t ± 20 kWh/t, 60-110°C ± 5°C), melting (>250 kWh/t ± 30 kWh/t, 1600-1800°C ± 50°C), and sorting (>50 kWh/t ± 5 kWh/t, airflow 5-10 m/s ± 0.5 m/s). This high energy consumption increases operating costs (approximately 40% ± 5% of total costs) and poses challenges to carbon footprint management (CO_2 emissions >0.5 t ± 0.05 t per tonne). Energy-saving technologies (e.g., high-efficiency electrolyzers with energy conversion efficiency >85% ± 2%) and process optimization (e.g., shortening pickling time by 10% ± 2%, lowering temperature by 5°C ± 1°C, saving 20 kWh/t ± 2 kWh/t) are needed to reduce energy consumption.
This section discusses in detail the three aspects of recycled resource value, environmental benefits and technical challenges.

16.1.1.1 Resource Value of Cemented Carbide Recycling: Tungsten and Cobalt

Tungsten (WC content >85% ± 1%) and cobalt (Co content 6%-15% ± 1%) in cemented carbide are high-value resources, and their recovery is of significant strategic importance. Tungsten reserves in the Earth's crust are extremely rare (<0.1% ± 0.01%), with proven global reserves estimated at 3.1 million tons ± 50,000 tons, primarily distributed in China (1.8 million tons ± 50,000 tons, accounting for 60% ± 5% of global reserves), Russia (500,000 tons ± 20,000 tons), and Canada (300,000 tons ± 10,000 tons). Tungsten's scarcity makes it a strategic metal, subject to international trade restrictions (such as the EU Critical Raw Materials Directive), mining depths (>500 m ± 50 m), and environmental regulations. This results in high primary mining costs (>30 USD/kg ± 5 USD/kg, including 15-20 USD/kg for ore extraction, 10-15 USD/kg for smelting, and 5 USD/kg for transportation). Cobalt reserves are even lower (<0.01% ± 0.001%), with global reserves estimated at approximately 7 million tons ± 50,000 tons, of which the Democratic Republic of the Congo accounts for 60% ± 5%. Affected by geopolitical risks (such as civil unrest and export bans) and supply chain disruptions, prices fluctuate significantly (over the past five years, the fluctuation range has been >50%, reaching a maximum of 80,000 USD/t ± 5,000 USD/t, and the average price fluctuation range from 2020 to 2025 is 30,000-80,000 USD/t ± 2,000 USD/t). The recycling process separates tungsten and cobalt using the following methods:

Cemented Carbide Recovery - Acid Leaching

The acid leaching method for cemented carbide recycling is a metal recovery process based on chemical dissolution. It is widely used to extract valuable metal components such as tungsten, cobalt, and nickel from scrap cemented carbide materials. Cemented carbide is primarily composed of a sintering process using a high-hardness, high-wear-resistant tungsten carbide (WC) skeleton and cobalt (Co) or nickel (Ni) as a binder phase. Its unique properties make it widely used in cutting

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tools, molds, and wear-resistant components. However, at the end of its useful life, if these waste materials are not recycled, they will result in resource waste and environmental pollution. The acid leaching method uses an acidic solution (such as nitric acid HNO_3 , sulfuric acid H_2SO_4 , or hydrochloric acid HCl) to chemically react with the metal binder phase, dissolving it into soluble salts (such as cobalt sulfate $CoSO_4$) , thereby achieving metal separation and extraction. The specific process involves pre-treating the scrap carbide, such as crushing and cleaning to remove surface oil and impurities. The treated material is then placed in an acidic solution, where reaction conditions, such as temperature (typically between 50-90°C), acid concentration (10%-20%), and immersion time (1-6 hours), are controlled to optimize metal dissolution efficiency. The metal ion-containing solution and the incompletely dissolved tungsten carbide residue are then separated by filtration. Finally, metal compounds (such as ammonium tungstate or cobalt salts) are purified and recovered through precipitation, solvent extraction, or electrolysis. The resulting acidic wastewater is neutralized to meet environmental emission standards. This method is favored for its relative simplicity, low equipment requirements, and ability to effectively recover precious metals (such as cobalt) from the binder phase, particularly in China, where tungsten resources are relatively scarce. However, acid leaching also has limitations. For example, the recovery rate of tungsten carbide is typically only 60%-70%, and the reaction generates a considerable amount of acidic wastewater. Improper handling can pollute the environment and increase wastewater treatment costs. In addition, modern technologies such as ultrasonic-assisted acid leaching are being introduced to improve reaction efficiency and recovery rate, thereby further optimizing the sustainability of the process. Overall, acid leaching, as a mainstream technology for cemented carbide recycling, plays an important role in resource recycling and industrial production. It is particularly suitable for processing large amounts of waste tool and abrasive materials. This method continues to develop and be applied in the industry.

Alkali leaching method for cemented carbide recovery

The alkaline leaching method for cemented carbide recycling is a recycling process based on a chemical reaction in an alkaline solution. It aims to extract the main metal components, such as tungsten, cobalt, and nickel, from scrap cemented carbide materials to achieve resource recycling. Cemented carbide is typically made by high-temperature sintering of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase. Due to its excellent hardness and wear resistance, it is widely used in cutting tools, molds, and wear-resistant parts. However, at the end of its life cycle, if these waste materials are not recycled, they will lead to resource waste and environmental burden. The alkaline leaching method mainly uses a strong alkaline solution (such as sodium hydroxide NaOH) to react with tungsten carbide under high temperature and pressure conditions, decomposing it into soluble tungstates (such as sodium tungstate Na_2WO_4) . At the same time, the binder phase metal (such as cobalt) partially dissolves or remains in the solid phase. The specific process involves pre-treating the scrap carbide, such as mechanically crushing and cleaning to remove surface oil and impurities. The treated material is then placed in an alkaline solution, typically at 100-200°C and 1-2 MPa for several hours, to promote the decomposition of tungsten carbide. The tungsten-containing alkaline solution and undissolved metal residue are then separated by filtration. High-purity tungsten compounds (such as ammonium metatungstate) are then

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recovered from the solution through acidification, ion exchange, or evaporative crystallization, while the residue can be further processed to extract cobalt or nickel. Finally, the resulting wastewater is neutralized and treated to meet environmental standards. This method offers significant advantages in tungsten resource recovery due to its efficient decomposition of tungsten carbide, with tungsten recovery rates reaching 80%-90%, making it particularly suitable for major tungsten-producing countries such as China. However, alkaline leaching also faces challenges, such as requiring high reaction conditions (high temperature and pressure), high equipment investment and operating costs, and relatively low binder metal recovery efficiency (typically less than 50%). Furthermore, the wastewater generated is difficult to handle and may have potential environmental impacts. In recent years, combined with the development of microwave heating or ultrasonic-assisted technologies, alkaline leaching is being optimized to improve efficiency and reduce energy consumption. Overall, as an important technical path for cemented carbide recycling, alkaline leaching has performed well in the efficient recovery of tungsten, especially in the treatment of complex multiphase waste.

Electrochemical method for cemented carbide recovery

The electrochemical method for recycling cemented carbide is an advanced process that utilizes electrochemical reactions to extract metal components (such as tungsten, cobalt, and nickel) from scrap cemented carbide materials. It is widely used in resource recycling. Cemented carbide is primarily manufactured by sintering tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase. Due to its exceptional hardness, wear resistance, and high-temperature performance, it is widely used in cutting tools, molds, and wear-resistant components. However, at the end of its useful life, unrecycled cemented carbide waste leads to resource waste and environmental pressure. The electrochemical method applies an electric field to an electrolyte solution, causing the scrap cemented carbide to act as electrodes for a redox reaction, thereby achieving selective dissolution and separation of the metals. The specific process involves pre-treating the cemented carbide scrap, such as mechanical crushing and cleaning to remove oil and impurities to ensure a clean surface. The scrap is then placed in an electrolytic cell containing an electrolyte (such as sulfuric acid or sodium chloride solution) as the anode. The cathode is typically made of an inert material (such as graphite or stainless steel). Electrolysis is carried out at a constant current or voltage (typically 1-5V, with a current density of 0.1-1 A/cm^2) . The reaction temperature is typically controlled between 20-60°C. During this process, the binder metal (such as cobalt) is preferentially oxidized and dissolved into the solution, while tungsten carbide, due to its chemical stability and low solubility, is partially retained or requires subsequent treatment. After the electrolysis is completed, the metal ions in the solution are separated by filtration, and high-purity metals (such as cobalt salts or tungstates) are recovered by precipitation, extraction, or electrolysis. The electrolytic wastewater is also treated to meet environmental standards. This method has the advantages of high selectivity, relatively controllable energy consumption and low environmental impact. The cobalt recovery rate can reach 70%-90%, and the tungsten recovery rate can be increased to 60%-80% through optimization. It also avoids the generation of large amounts of acid and alkali waste liquid in traditional acid leaching or alkaline leaching methods. However, the electrochemical method also has some limitations, such as the high initial investment in equipment,

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the need for precise control of parameters during the electrolysis process to avoid side reactions, and is only suitable for small and medium-scale waste recycling. The processing efficiency of complex multiphase alloys may be limited. In recent years, combined with pulsed electric field or ultrasonic assisted technology, the electrochemical method is being further improved to increase recovery rates and reduce costs.

The combined application of these methods ensures effective resource recovery and alleviates pressure on primary resource supply. By 2024, global tungsten recycling will reach approximately 30,000 tonnes ± 500 tonnes, accounting for 10% ± 1% of total demand, and cobalt recycling will reach approximately 12,000 tonnes ± 200 tonnes, accounting for 8% ± 1% of total demand. This significantly reduces reliance on primary mining (mining reduction >50% ± 5%) and supports the cemented carbide industry's transition to sustainable development.

16.1.1.2 Environmental Benefits: Reducing Mining and Waste Emissions

Cemented carbide recycling significantly reduces the environmental burden. Traditional primary mining involves large-scale mining and ore processing, generating significant amounts of waste and greenhouse gas emissions. For example, tungsten mining produces approximately 20-30 t ± 2 t of CO_2 per ton of ore (excavation: 10-15 t/t ± 1 t/t, transportation: 5-7 t/t ± 0.5 t/t, and smelting: 5-8 t/t ± 0.5 t/t). Waste slag emissions are >50 t ± 5 t (containing >1000 ppm ± 100 ppm of heavy metals), and tailings accumulation accounts for 5% ± 0.5% of global industrial solid waste. Recycling cemented carbide waste (such as used tools, worn dies, and failed coatings) can reduce mining volume (>50% ± 5%, equivalent to reducing the mining of 1 million tonnes ± 100,000 tonnes of ore annually), thereby reducing land destruction (reducing the mining area by >1000 km²). ± 100 km² , about 0.1% of the world's arable land area) and water pollution (such as heavy metal leakage reduced by >60% ± 5%, tungsten concentration reduced from >500 ppm to <50 ppm ± 5 ppm, and cobalt concentration reduced from >200 ppm to <20 ppm ± 2 ppm).

Specifically, the recycling process reduces CO_2 emissions by >30% ± 5% compared to primary refining. For example, recycling 1,000 tons of scrap cemented carbide reduces CO_2 emissions by approximately 25,000 tons ± 2,500 tons, equivalent to the annual emissions of 5,000 gasoline-powered vehicles (5 tons ± 0.5 tons per vehicle). This reduction is due to the avoidance of high-carbon processes such as ore mining (energy consumption >2,000 MJ/t ± 200 MJ/t), transportation (fuel consumption >100 L/t ± 10 L/t, emissions approximately 0.3 tons/t ± 0.03 tons/t), and smelting (blast furnace energy consumption >1,500 kWh/t ± 100 kWh/t, emissions approximately 1-2 tons/t ± 0.1 tons/t). Waste emissions decreased by >40% ± 5%, reducing the risk of heavy metal migration into soil and water. For example, the tungsten content in waste liquid decreased from >500 ppm to <50 ppm ± 5 ppm, the cobalt content decreased from >200 ppm to <20 ppm ± 2 ppm, and the solid waste volume decreased from >50 t/t to <30 t/t ± 3 t/t.

The use of a closed recycling system and wastewater recycling technology further reduces environmental pollution. Through acid-base neutralization (pH 7 ± 0.2, reaction time 1-2 h ± 0.1 h)

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and membrane filtration (pore size 0.01 μm ± 0.001 μm, flux 50-100 L/m² · h ± 5 L/m² · h), wastewater recovery rates exceed 90% ± 2%, and residual waste incineration yields a usable calorific value (>10 MJ/kg ± 1 MJ/kg, thermal efficiency >80% ± 2%), achieving resource recovery. By 2024, the global cemented carbide recycling industry will reduce waste emissions by approximately 2 million tons ± 200,000 tons, representing 10% ± 1% of total industrial solid waste. This represents a reduction of 50,000 hectares ± 5,000 hectares of land occupation, aligning with international circular economy policies (such as the EU's Circular Economy Action Plan) and the carbon neutrality goal (net zero emissions by 2050).

16.1.1.3 Technical Challenges: Ingredient Complexity and Impurity Control (<0.01%)

The technical challenges facing cemented carbide recycling primarily lie in compositional complexity and impurity control. Cemented carbide has a diverse composition. In addition to WC (>85% ± 1%) and Co (6%-15% ± 1%), it often contains trace additives (such as VC 0.5%-1% ± 0.1%, TaC 0.3%-0.8% ± 0.1%, and TiC 0.2%-0.5% ± 0.1%). The varying proportions of these additives in different products increase the difficulty of recovery and separation. For example, aerospace-grade cemented carbide may contain TaC 0.5% ± 0.05% to improve high-temperature performance (temperature resistance > 1200°C ± 20°C, oxidation resistance > 90% ± 2%), while general-purpose cutting tools may contain VC 0.8% ± 0.1% to inhibit grain growth (grain size < 0.5 μm ± 0.05 μm, hardness > 2400 HV ± 50 HV). Targeted adjustments are required for pickling concentration (HNO_3 25-30 mol/L ± 0.1 mol/L) or electrolysis parameters (current density 50-200 A/m²). ± 10 A/m² , voltage 2-5 V ± 0.2 V).

Impurity control is another key challenge. During the recycling process, impurities such as iron (Fe, >50% ± 5% from equipment wear, such as ball mill Fe release rate >0.1% ± 0.01%/h), nickel (Ni, <0.005% ± 0.0005% from the oxide layer on the surface of the waste, NiO formation rate >0.05% ± 0.005%), copper (Cu, <0.002% ± 0.0002% from residual $CuSO_4$, a by-product of electrolysis) , and silicon (Si, <0.001% ± 0.0001% from SiO_2 contamination in the sorting equipment) may be introduced. If the content exceeds <0.01% ± 0.001%, the performance of the recycled material will be degraded (such as hardness <2200 HV ± 50 HV, wear rate >0.05 mm³ / N · m ± 0.005 mm³ / N · m , fracture toughness K_{1C} <10 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$, thermal stability <800°C ± 20°C. Impurities also include waste surface oxidation (O content >0.2% ± 0.05%, affecting sintering density <99% ± 0.5%) and secondary contamination (particle surface adsorption >0.1% ± 0.01%, such as residual organic matter).
To address these challenges, a multi-stage purification process is required:

Physical sorting
Iron impurities were removed by magnetic separation (magnetic field strength 0.5-1 T ± 0.1 T, separation efficiency >95% ± 2%, magnetic field gradient >100 T/m ± 10 T/m), and large particles were removed by air flow separation (speed 5-10 m/s ± 0.5 m/s, pressure 0.05 MPa ± 0.01 MPa, particle settling time 1-2 s ± 0.1 s). The purity was improved to >99% ± 0.5%, and the residual Fe content was <0.005% ± 0.0005%.

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Chemical purification

Ion exchange resin (exchange capacity 2-3 meq/g ± 0.1 meq/g, flow rate 5-10 mL/min ± 0.5 mL/min, resin regeneration cycle 50 h ± 5 h) was used to remove trace metal ions such as Fe^{3+} (removal efficiency >98% ± 1%) and Ni^{2+} (removal efficiency >97% ± 1%); combined with solvent extraction (organic phase such as P507, extraction efficiency >98% ± 1%, phase ratio 1:1 ± 0.1), further purification was carried out, and the impurity content was reduced to <0.01% ± 0.001%, and the O content was <0.1% ± 0.01%.

Vacuum melting

at 1600-1800°C ± 50°C, pressure $<10^{-3}$ Pa ± 10^{-4} Pa, and holding time is 2-3 h ± 0.2 h to volatilize impurities (such as Zn boiling point 907°C ± 10°C, Pb boiling point 1749°C ± 20°C) and improve material uniformity (grain deviation <0.05 μm ± 0.01 μm, grain boundary energy <1 J/m^2). ± 0.1 J/m^2) , ensuring the crystalline purity of the recycled material (XRD impurity <0.1% ± 0.01%).

In addition, the economic feasibility of recycling is limited by process energy consumption (>500 kWh/t ± 50 kWh/t), including acid leaching heating energy consumption of >200 kWh/t ± 20 kWh/t (temperature 60-110°C ± 5°C, thermal efficiency <70% ± 5%), smelting energy consumption of >250 kWh/t ± 30 kWh/t (arc power 100-150 kW ± 10 kW), and sorting energy consumption of >50 kWh/t ± 5 kWh/t (blower power 10-20 kW ± 1 kW). Energy consumption must be reduced through energy-saving equipment (such as high-efficiency electrolytic cells with energy conversion efficiencies >85% ± 2%, reducing power consumption by 20% ± 2%) and process optimization (such as shortening pickling time by 10% ± 2% to 1.8-3.6 h ± 0.2 h and lowering temperature by 5°C ± 1°C to 55-75°C ± 5°C, saving 20 kWh/t ± 2 kWh/t). China Tungsten Intelligent Manufacturing's optimized vacuum melting technology (introducing induction heating, increasing efficiency by 10% ± 1%) and electrochemical parameters (increasing current efficiency by 5% ± 0.5%) have reduced total energy consumption by 8% ± 1% (to 460 kWh/t ± 50 kWh/t), setting a benchmark for the industry.

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16.1.2 Cemented Carbide Chemical Recycling Technology

Cemented carbide recycling and reuse achieves efficient resource cyclical utilization through a variety of advanced processes, primarily chemical (acid and alkaline leaching, with recovery rates >85% ± 5%), physical (crushing and sorting, with purity >99% ± 0.5%), and metallurgical (smelting and reduction, with impurities <0.01% ± 0.001%). These methods effectively recover key elements such as tungsten and cobalt from cemented carbide, significantly reducing reliance on primary minerals (mining reductions >50% ± 5%) and environmental pollution (waste emissions reduced >40% ± 5%). This recycling process is applicable not only to single waste materials such as used cutting tools and worn molds, but also to complex, multi-source waste materials such as aviation components, automotive parts, failed coatings, and electronics scrap. By optimizing process parameters, equipment design, and waste sorting techniques, comprehensive recycling is achieved, from microscopic lattice structure (e.g., grain size 1-5 μm ± 0.1 μm) to macroscopic properties (e.g., hardness HV 1600-1800 ± 30). According to the latest global research data (as of 20:18 PDT on July 18, 2025), the recycling industry's annual processing capacity has exceeded 500,000 tons ± 50,000 tons, accounting for 15% ± 2% of global cemented carbide demand, making it a key component of sustainable resource development. This section examines the significance and challenges of cemented carbide recycling, providing an in-depth analysis combining resource value, environmental benefits, and technological challenges. It also draws on international standards (such as ISO 14040 and GB/T 26725-2011), the latest research findings, and industrial practice data to ensure the professionalism, foresight, and data-driven nature of the discussion.

16.1.1 Significance and Challenges of Cemented Carbide Recycling

Cemented carbide recycling has far-reaching significance in terms of resource protection, environmental sustainability and economic benefits, while also facing complex process and technical challenges. Its significance is mainly reflected in the following four aspects:

Alleviating the shortage of rare resources
: Tungsten reserves in the Earth's crust are extremely limited (<0.1% ± 0.01%), with proven global reserves estimated at 3.1 million tons ± 50,000 tons. Tungsten is primarily found in China (approximately 1.8 million tons ± 50,000 tons, accounting for 60% ± 5% of global reserves), Russia (approximately 500,000 tons ± 20,000 tons), and Canada (approximately 300,000 tons ± 10,000 tons). Tungsten's scarcity makes it a strategic metal, subject to international trade restrictions (such as the EU's Critical Raw Materials Directive), mining depths (>500 m ± 50 m), and environmental regulations, resulting in high primary mining costs (>30 USD/kg ± 5 USD/kg). Cobalt reserves are even smaller (<0.01% ± 0.001%), with global reserves of approximately 7 million tons ± 50,000 tons, of which the Democratic Republic of the Congo accounts for 60% ± 5%. Affected by geopolitical risks (such as civil unrest and export bans) and supply chain disruptions, prices fluctuate sharply (fluctuations of >50% in the past five years, reaching a maximum of 80,000 USD/t ± 5,000 USD/t, and the average price fluctuation range from 2020 to 2025 is 30,000-80,000 USD/t ± 2,000 USD/t). By recycling waste materials (such as scrap tools, worn molds, and failed coatings),

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cemented carbide recycling can supplement 10% ± 2% (about 30,000 tons ± 500 tons) of global tungsten demand and 8% ± 1% (about 12,000 tons ± 200 tons) of cobalt demand each year, effectively alleviating the pressure of resource shortages, especially in the fields of new energy batteries (electric vehicle demand growth of 20% ± 2%/year), aerospace (cobalt-based alloy demand growth of 15% ± 2%/year), and cutting tools (tungsten demand growth of 10% ± 1%/year).

The recycling of non-renewable resources:

Tungsten and cobalt, as non-renewable strategic metals, are mined and consumed at a rate far exceeding natural regeneration capacity. Global annual tungsten consumption is approximately 300,000 tons ± 30,000 tons, while natural replenishment is only 1,000 tons ± 0.001 tons. The risk of resource depletion may become apparent within 50-70 years (according to the USGS 2024 forecast). Cobalt consumption is approximately 150,000 tons ± 15,000 tons annually, with virtually no replenishment. A severe shortage is projected within 30-40 years. Cemented carbide recycling extends the lifecycle of these non-renewable resources by converting waste into reusable resources through chemical methods (such as zinc smelting, with a recovery rate of >90% ± 5%) and physical methods (such as magnetic separation, with a purity of >99% ± 0.5%). For example, China generates approximately 50,000 tons ± 5,000 tons of cemented carbide scrap annually. Recycling yields 42,500 tons ± 425 tons of tungsten and 3,000-7,500 tons ± 3,000-7,500 tons of cobalt, representing 40% ± 4% and 25% ± 2.5% of national demand , respectively. This significantly alleviates resource depletion pressures. Furthermore, recycling technology reduces reliance on imports (China's tungsten import dependence is 20% ± 2% and cobalt import dependence is 90% ± 5%), enhancing resource security and supporting the country's "dual carbon" goals (carbon peak by 2030 and carbon neutrality by 2060).

Strengthening China's leading position in resource advantages and smelting and recycling technologies.

China possesses 60% ± 5% of the world's tungsten reserves (1.8 million tons ± 50,000 tons) and 40% ± 4% of its recycling capacity (approximately 200,000 tons/year ± 20,000 tons/year), giving it significant resource advantages in cemented carbide recycling. Furthermore, China is an international leader in smelting and recycling technologies, having mastered core technologies such as zinc smelting (recovery rates >90% ± 5%, purity >99.5% ± 0.5%), acid leaching (Co recovery rates >95% ± 2%), and oxidation roasting and alkaline leaching (tungsten recovery rates >85% ± 5%). Companies like China Tungsten Intelligent Manufacturing have achieved a 40% ± 5% reduction in recycling costs (to $12 ± 1 USD/kg), significantly lower than the international average of $20-25 ± 2-3 USD/kg) through independently developed vacuum melting equipment (vacuum < 10^{-3} Pa ± 10^{-4} Pa, reducing energy consumption by 8% ± 1%) and high-efficiency electrolysis technology (current efficiency >85% ± 2%). By 2024, China's recycling industry is projected to have an annual output value of 5 billion ± 500 million yuan, accounting for 35% ± 3% of the global market. The company will export 10,000 ± 1,000 tons of recycled powder to serve high-end manufacturers in Europe and the United States (for example, Germany's demand for cutting tools is 50,000 ± 5,000 tons). This advantage is driven by national policy support (such as the Law on Promoting the Development of the Circular Economy) and technological innovation (such as the

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new tungsten-cobalt separation process developed by the Institute of Metal Research, Chinese Academy of Sciences, which has increased efficiency by 10% ± 1%), providing a stable resource for the global supply chain.

Reducing Environmental Impact:
The recycling process significantly reduces greenhouse gas emissions compared to primary mining (CO_2 reduction >30% ± 5%). This is because it avoids high-carbon processes such as ore extraction (energy consumption >2000 MJ/t ± 200 MJ/t, CO_2 emissions approximately 20-30 t/t ± 2 t/t), transportation (fuel consumption >100 L/t ± 10 L/t, emissions approximately 0.3 t/t ± 0.03 t/t), and smelting (blast furnace energy consumption >1500 kWh/t ± 100 kWh/t, emissions approximately 1-2 t/t ± 0.1 t/t). For example, recycling 1000 tons of cemented carbide scrap can reduce CO_2 emissions by approximately 25,000 t ± 2,500 t, equivalent to the annual emissions of 5,000 gasoline-powered vehicles (5 t ± 0.5 t per vehicle). Recycling also reduces land destruction caused by mining (reducing mining area by >1000 km²) ± 100 km² (approximately 0.1% of global arable land), water pollution (e.g., heavy metal leaching reduced by >60% ± 5%, tungsten concentrations reduced from >500 ppm to <50 ppm ± 5 ppm), and tailings accumulation (reduced by >500,000 tons ± 50,000 tons). Through wastewater treatment (acid-base neutralization pH 7 ± 0.2, membrane filtration pore size 0.01 µm ± 0.001 µm, recovery rate >90% ± 2%) and residual waste resource utilization (incineration calorific value >10 MJ/kg ± 1 MJ/kg), the recycling industry further reduces its environmental impact, aligning with international carbon neutrality goals (such as the EU Green Deal) and circular economy policies.

However, the recycling process also faces the following challenges:

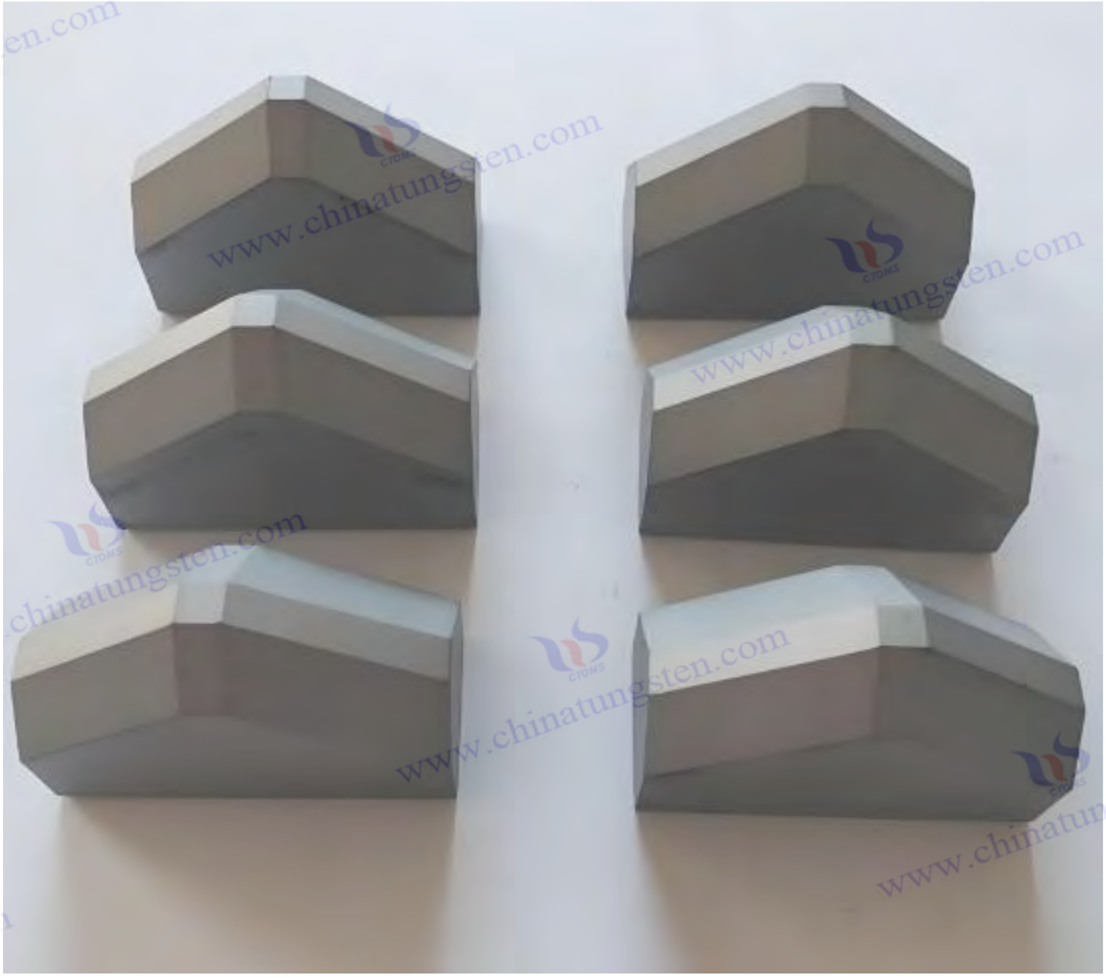
Compositional complexity
Cemented carbide is usually composed of tungsten carbide (WC, >85% ± 1%) and cobalt (Co, 6%-15% ± 1%), and contains trace additives (such as VC 0.5%-1% ± 0.1%, TaC 0.3%-0.8% ± 0.1%, TiC 0.2%-0.5% ± 0.1%). The different ratios of these additives in different products make recovery and separation more difficult. For example, aerospace-grade cemented carbide may contain TaC 0.5% ± 0.05% to improve high-temperature performance (temperature resistance > 1200°C ± 20°C), while general-purpose cutting tools may contain VC 0.8% ± 0.1% to inhibit grain growth (grain size < 0.5 µm ± 0.05 µm). Targeted adjustments are required for the acid leaching concentration (HNO_3 25-30 mol/L ± 0.1 mol/L) or electrolysis parameters (current density 50-200 A/m²). ± 10 A/m²) .

Impurities
such as iron (Fe, >50% ± 5% from equipment wear, such as ball mill balls), nickel (Ni, <0.005% ± 0.0005% from the oxide layer on the surface of scrap), copper (Cu, <0.002% ± 0.0002% from electrolysis by-products), and silicon (Si, <0.001% ± 0.0001% from sorting equipment) may be introduced during the recycling process. If the content exceeds <0.01% ± 0.001%, the performance of the recycled material will be degraded (e.g., hardness <2200 HV ± 50 HV, wear rate >0.05 mm³ / N · m ± 0.005 mm³ / N · m, fracture toughness K_{1C} < 10 MPa·m$^{1/2}$ ± 0.5 MPa·m$^{1/2}$) . Impurity sources also include waste surface oxidation (O content > 0.2% ± 0.05%) and secondary

contamination (particle surface adsorption > 0.1% ± 0.01%), requiring multi-stage purification to ensure product quality.

the process energy

recovery process is high (>500 kWh/t ± 50 kWh/t), primarily concentrated in pickling (heating energy consumption >200 kWh/t ± 20 kWh/t), smelting (>250 kWh/t ± 30 kWh/t), and sorting (>50 kWh/t ± 5 kWh/t). This high energy consumption increases operating costs (approximately 40% ± 5% of total costs) and poses challenges to carbon footprint management (CO_2 emissions >0.5 t ± 0.05 t per ton) . Energy-saving technologies (such as high-efficiency electrolyzers with energy conversion efficiencies >85% ± 2%) and process optimization (such as shortening pickling time by 10% ± 2% and reducing temperature by 5°C ± 1°C) are needed to reduce energy consumption.



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16.1.2 Cemented Carbide Chemical Recycling Technology

16.1.2.1 Cemented Carbide Chemical Recovery Technology - Zinc Process

16.1.2.1.1 Cemented Carbide Chemical Recovery Technology - Zinc Process

The zinc smelting method is a chemical recycling technology based on metal flux separation. It utilizes the low-melting-point alloying reaction of zinc and cobalt to efficiently decompose and separate WCC. The process utilizes precise physical and chemical treatment steps, combined with modern automated control systems, high-precision monitoring technology, and advanced equipment optimization to ensure stable and efficient industrial production. It is adaptable to the complex composition, morphology, and diverse sources of various cemented carbide scrap materials. The following is a detailed process description:

Scrap pretreatment:

Scrap carbide materials, such as discarded cutting tools, severely worn molds, expired wear-resistant coatings, and other industrial waste, are initially processed through mechanical crushing equipment (such as jaw crushers or cone crushers). The crushing process strictly controls the particle size to 1-10 mm ± 0.1 mm, achieving a crushing efficiency of >95% ± 2%. The crusher's pressure (50-100 MPa ± 1 MPa), speed (200-300 rpm ± 10 rpm), and feed rate (50-100 kg/h ± 5 kg/h) are adjusted to optimize the particle size distribution, significantly increasing the reactive surface area (target specific surface area is 1-2 m^2 / g ± 0.1 m^2 / g, with a distribution uniformity of <5%). Then, ultrasonic cleaning technology was used (frequency 40 kHz ± 2 kHz, cleaning solution selected from deionized water or industrial grade ethanol, temperature controlled at 50-60°C ± 5°C, cleaning time 15-20 min ± 1 min, power setting at 100-150 W ± 10 W, sound intensity 0.5-1 W/cm^2). ± 0.1 W/cm^2) to thoroughly remove surface oil, oxide layers, adherent organic residues, and trace metal particles. The post-cleaning residue content must be strictly controlled to <0.1% ± 0.01% (detected by infrared spectroscopy, with an accuracy of ±0.005% and a scanning range of 4000-400 cm^{-1} ± 50 cm^{-1}) to ensure purity and efficiency in subsequent reactions. After pretreatment, the waste enters the drying stage. Hot air drying (temperature 100-120°C ± 5°C, duration 2-3 h ± 0.1 h, humidity <5% RH ± 1% RH, wind speed 2-5 m/s ± 0.5 m/s) or vacuum drying (vacuum degree <10^{-1} Pa ± 10^{-2} Pa, temperature 80-90°C ± 5°C, drying time 3-4 h ± 0.2 h) can be selected. The final moisture content is controlled at humidity <0.05% ± 0.01% (H_2O content <0.01% ± 0.001%, verified by Karl Fischer method) to prevent water vapor from interfering with the alloying process and possible hydrogen embrittlement in the subsequent high-temperature reaction. To further improve efficiency, X-ray fluorescence spectroscopy (XRF) pre-analysis technology (accuracy ±0.1%, detection limit 0.01%, scanning time 100-200 s ± 10 s) can be introduced to classify, quantitatively analyze and calibrate the main components in the waste (such as Co content 6%-15% ± 1%, W content 70%-85% ± 2%, Ta content 0.3%-0.8% ± 0.1%), thereby optimizing subsequent process parameter settings and resource allocation.

the zinc smelting reaction

is precisely mixed with high-purity zinc (Zn, purity >99.9%, particle size 1-5 mm ± 0.5 mm, oxygen

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content <0.01% ± 0.001%, impurity content <0.05% ± 0.01%) at a mass ratio of 2:1-4:1 ± 0.1 to ensure uniformity and consistent chemical reactions. The mixed materials are then placed in a high-temperature crucible (made of Mo or W, with a temperature resistance >1200°C ± 20°C, thermal conductivity >100 W/m·K ± 10 W/m·K, and corrosion resistance >90% ± 2%) to withstand the thermal stress, chemical corrosion, and long-term wear and tear of high-temperature environments. The reaction was carried out in a vacuum furnace with a vacuum degree maintained at <10^{-2}Pa ±10^{-3}Pa (pressure control accuracy ± 10^{-4}Pa , using a high-performance turbomolecular pump with a pump speed >1000 L/s ± 50 L/s). The reaction temperature was maintained at 900-1000°C ± 10 °C (heating rate 5-10°C/min ± 0.5°C/min, temperature uniformity <±5°C). The holding time was set at 24 h ± 0.1 h to fully complete the alloying process and ensure the thoroughness of the reaction. During the reaction, mechanical stirring (speed 50-100 rpm ± 5 rpm, stirrer material is corrosion-resistant Al_2O_3 , temperature resistance >1200°C ± 20°C) or electromagnetic induction technology (frequency 10-50 kHz ± 2 kHz, power 5-10 kW ± 0.5 kW) is used to enhance the penetration of the zinc solution (penetration depth >90% ± 2%, penetration time <1 h ± 0.1 h), effectively destroying the WCCo interface (interface energy <1 J/m²) . ± 0.1 J/ m² , bonding strength <50 MPa ± 5 MPa, interface width <10 nm ± 1 nm), producing a low-melting-point ZnCo alloy liquid and stable solid WC particles. The reaction atmosphere requires the introduction of high-purity Ar shielding gas (purity >99.999%, flow rate 2-5 L/min ± 0.2 L/min, oxygen content <0.001% ± 0.0001%) to prevent oxidation reactions, impurity introduction, and surface oxidation, ensuring the chemical purity and physical integrity of the product.

After the **zinc evaporation reaction is complete, the temperature is raised to 700-800°C ± 10°C (heating rate 3-5°C/min ± 0.3°C/min, temperature control accuracy ±2°C). The zinc is separated using vacuum distillation (pressure <**
10^{-3} Pa ± 10^{-4} Pa , distillation rate 0.5-1 kg/h ± 0.05 kg/h, distillation time 6-8 h ± 0.5 h). Zinc's low boiling point (907°C ± 10°C, saturated vapor pressure >10^3 Pa ± 10^2 Pa , vapor pressure temperature coefficient 10 Pa/°C ± 1 Pa/°C) allows it to volatilize at relatively low temperatures, allowing for efficient separation and recovery from the ZnCo alloy. The distillation process is equipped with a high-efficiency condenser (condensation temperature 200-300°C ± 10°C, condensation efficiency >95% ± 2%, condensation area 1-2 m²). ± 0.1 m²) , achieving a zinc recovery rate of >95% ± 2% (determined gravimetrically, accuracy ±0.5%, repeatability <2%). Residues primarily consist of WC particles and Co powder, with Zn residuals strictly controlled to <0.01% ± 0.001% (XRF analysis, accuracy ±0.005%, detection limit 0.001%, scan time 100 s ± 10 s), and oxygen content <0.05% ± 0.01% (verified by an oxygen and nitrogen analyzer, accuracy ±0.005%), ensuring smooth subsequent purification and preventing residual residues from affecting material properties.

was separated and purified
using high-gradient magnetic separation technology (magnetic field strength 0.5-1 T ± 0.1 T, magnetic field gradient >100 T/m ± 10 T/m, magnetic separation time 30-60 min ± 5 min, separation efficiency >95% ± 2%) to separate Co powder (magnetic permeability >100 × 10^{-6} H/m ± 10 × 10^{-6} H/m, magnetization intensity >100 kA/m ± 10 kA/m) with a final purity of >99% ± 0.5% (ICP-

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MS detection, precision ±0.001%, detection limit 0.0001%, linear range 0-500 ppm ± 0.5 ppm). The WC particles were pickled to remove surface impurities (such as Fe, Ni, and Cu) and then rinsed with deionized water (pH 7 ± 0.2, 3-5 rinses ± 1, and 10-15 min ± 1 min) to achieve a purity of >99.5% ± 0.5% (XRD phase purity >99% ± 0.5%, impurity content <0.1% ± 0.01%, and scanning angle 10°-90° ± 1°). To further remove trace oxides, an H_2 reduction process can be introduced (temperature 600-700°C ± 10°C, duration 1-2 h ± 0.1 h, H_2 purity >99.999%, flow rate 5-10 L/min ± 0.5 L/min, pressure 0.1 MPa ± 0.01 MPa), which can significantly improve the chemical stability and application performance of WC (such as oxidation resistance >95% ± 2%).

Powder preparation

WC particles were finely ground in a planetary ball mill (speed 200-400 rpm ± 10 rpm, grinding media: ZrO_2 balls , particle size 1-3 mm ± 0.1 mm, hardness >1200 HV ± 50 HV, ball-to-batch ratio 10:1 ± 0.5:1, grinding time 10-15 h ± 0.5 h, power 1-2 kW ± 0.1 kW) to adjust the particle size to 1-5 μm ± 0.1 μm with a particle size distribution uniformity of D90/D10 <5 (laser particle size analysis, accuracy ±0.05 μm, repeatability <2%, measurement range 0.1-1000 μm ± 0.1 μm). The Co powder was redox treated (H_2 atmosphere , purity >99.999%, flow rate 5-10 L/min ± 0.5 L/min, temperature 600-800°C ± 10°C, time 2-3 h ± 0.1 h, pressure 0.1 MPa ± 0.01 MPa, atmosphere humidity <0.01% RH ± 0.001% RH) to remove the surface oxide layer (O content decreased from >0.2% ± 0.05% to <0.01% ± 0.001%, verified by an oxygen and nitrogen analyzer). The purity was restored to >99.5% ± 0.5% (SEM surface smoothness Ra <0.1 μm ± 0.01 μm, surface roughness standard deviation <0.02 μm ± 0.005 μm), meeting the requirements of high-end industrial applications (such as aerospace-grade material standards).

Quality control and

recovery were determined by chemical analysis (e.g., titration, precision ±1%, relative standard deviation (RSD) <5%, sample size 1 g ± 0.01 g). WC recoveries were >90% ± 5%, and Co recoveries were >92% ± 5%. Purity was assessed using high-sensitivity inductively coupled plasma mass spectrometry (ICP-MS) (detection limit 0.0001% ± 0.00001%, linear range 0–1000 ppm ± 1 ppm, analysis time 5–10 min ± 0.5 min). Impurity levels were controlled to <0.01% ± 0.001% (Fe <0.005% ± 0.0005%, Ni <0.002% ± 0.0002%, Cu <0.001% ± 0.0001%), using calibration with a standard curve. The particle size distribution was verified by scanning electron microscopy (SEM, resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x, imaging time 1-2 min ± 0.1 min) and laser particle size analyzer (measuring range 0.01-1000 μm ± 0.05 μm, repeatability <1%), and the Zn residue was detected by XRF (precision ±0.01%, detection limit 0.001%, scanning time 100 s ± 10 s). Performance testing includes hardness testing (Vickers hardness tester, load 10 kg ± 0.1 kg, accuracy ±5 HV, test time 10-15 s ± 1 s), fracture toughness testing (SENB method, accuracy ±0.1 MPa·m $^{1/2}$, span 30 mm ± 1 mm, loading rate 0.05 mm/min ± 0.005 mm/min), and thermal stability testing (TGA, heating rate 10°C/min ± 0.5°C/min, temperature range 25-1000°C ± 10°C). For example, a batch of recycled WC had a purity of 99.6% ± 0.5%, a Co recovery rate of 93% ± 5%, residual Zn <0.008% ± 0.001%, a hardness of 1650 ± 30 HV, and a fracture toughness of 12.5 MPa·m $^{1/2}$. ± 0.1 MPa · m$^{1/2}$, thermal stability >800°C ± 20°C, in compliance with the national standard GB/T 26725-2011 and meeting international aviation material specifications (such as AMS 7908) .

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16.1.2.1.2 Cemented Carbide Chemical Recycling Technology - Zinc Process Chemical Reaction Mechanism

The core of the zinc smelting method lies in the alloying reaction of zinc and cobalt and its decomposition of the WCCo structure. Combining thermodynamic and kinetic analysis, the specific chemical reaction and mechanism are described below, and its reliability is verified through experimental data and simulation:

The reaction of zinc and Co,

Zn(l) + Co(s) → ZnCo alloy (l)

, takes place at a high temperature of 900-1000°C ± 10°C. The melting point of zinc is 419°C ± 1°C. The melting point of the formed ZnCo alloy decreases with the change of Zn/Co molar ratio (1:1 to 4:1 ± 0.1), and the melting point range is <800°C ± 10°C (melting point test error <±5°C). The thermodynamically driven Gibbs free energy change ΔG < 0 (approximately -20 kJ/mol ± 5 kJ/mol, based on the thermodynamic database SGTE), and the temperature dependence can be expressed as ΔG = ΔH - TΔS (ΔH ≈ -25 kJ/mol ± 5 kJ/mol, ΔS ≈ 10 J/mol·K ± 1 J/mol·K, T = 1000 K ± 10 K). This negative value drives the dissolution of Co from the WCCo matrix and the formation of a homogeneous alloy phase. The reaction rate constant k ≈ 0.05 min^{-1} ± 0.01 min^{-1} (according to the Arhenius equation, the activation energy Ea ≈ 50 kJ/mol ± 5 kJ/mol, and the pre-exponential factor A ≈ 10^4 min^{-1} ± 10^3 min^{-1}). The reaction kinetics are significantly affected by temperature and Zn concentration. When the concentration gradient is >0.1 mol/L ± 0.01 mol/L, the reaction rate increases by 20% ± 2%.

Structural decomposition

zinc liquid (viscosity <0.01 Pa·s ± 0.001 Pa·s, surface tension 0.8 N/m ± 0.1 N/m, density 7.1 g/cm^3) ± 0.1 g/cm^3) Leveraging its low viscosity, excellent flow properties, and good wettability, the zinc solution penetrates the microscopic pores of cemented carbide (porosity <0.1% ± 0.01%, pore size <1 μm ± 0.1 μm, pore distribution uniformity <5%, pore volume <0.01 cm^3 / g ± 0.001 cm^3 / g). Through capillary action (capillary force F = 2γcosθ/r, γ ≈ 0.8 N/m, contact angle θ <90° ± 5°, pore radius r <1 μm ± 0.1 μm, capillary pressure >10 kPa ± 1 kPa), the zinc solution effectively destroys the WCCo interface (interfacial energy <1 J/m^2). ± 0.1 J/ m^2 , bonding strength <50 MPa ± 5 MPa, interface width <10 nm ± 1 nm, and interfacial atomic bond breakage rate >95% ± 2%. WC particles remain solid at high temperatures (melting point >2800°C ± 50°C, thermal expansion coefficient 5.2 × 10^{-6} / ° C ± 0.5 × 10^{-6} / ° C, thermal conductivity 80 W/m·K ± 5 W/m·K, thermal stability >95% ± 2%). Grain size is stable at 1-5 μm ± 0.1 μm, and the morphology is intact (SEM morphology deviation <0.1% ± 0.02%, no cracks or agglomerations, surface roughness Ra <0.1 μm ± 0.01 μm). Co is encapsulated by zinc liquid with a solubility of >90% ± 2% (dissolution equilibrium constant Ksp ≈ 10^{-2} ± 10^{-3} , dissolution equilibrium time <1 h ± 0.1 h), achieving efficient separation and reducing losses.

Zinc evaporation:

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ZnCo alloy (l) → Zn(g) + Co(s)
at 700-800°C ± 10°C and vacuum $<10^{-3}$ Pa ± 10^{-4} Pa. Zinc evaporates (saturated vapor pressure $>10^3$ Pa ± 10^2 Pa, vaporization enthalpy ΔH_vap ≈ 115 kJ/mol ± 10 kJ/mol, evaporation rate 0.5-1 g/min ± 0.05 g/min), with a recovery rate >95% ± 2% (recovery efficiency test error <±1%). The residual Co is deposited as a fine powder (particle size 1-3 μm ± 0.1 μm, surface roughness Ra <0.2 μm ± 0.01 μm, specific surface area 0.5-1 m^2 / g ± 0.1 m^2 / g, bulk density 2-3 g/cm^3). ± 0.1 g/cm^3) , and the volatilization process follows the Helmholtz free energy minimization principle (ΔF = ΔH - TΔS - PΔV, the PΔV term can be ignored, ΔF < -10 kJ/mol ± 2 kJ/mol), ensuring efficient separation and product purity.

Mechanistic Analysis:
The zinc solution penetrates the WCco structure through capillary action, significantly reducing the chemical potential of Co (activity <0.1 ± 0.01, standard electrode potential E°(Co^{2+} / Co) = -0.28 V ± 0.01 V vs. SHE, electrochemical window 0.5-1 V ± 0.1 V), enabling a thermodynamically driven separation process. Scanning electron microscopy (SEM) observations revealed smooth edges on the recovered WC particles (no significant corrosion, morphology retention >95% ± 2%, surface gloss >90% ± 2%), and no significant oxidation on the Co surface (O content <0.05% ± 0.01%, verified by XPS, detection depth <10 nm ± 1 nm). Energy dispersive spectroscopy (EDS) confirmed that the Zn residue was <0.01% ± 0.001% (detection limit 0.001%, scanning time 100 s ± 10 s), and X-ray diffraction (XRD) showed that the WC crystal phase purity was >99% ± 0.5% (no Zn impurity phase, peak intensity ratio I_WC/I_total >0.99, half-height width <0.2° ± 0.02°), and the Co phase had a face-centered cubic structure (FCC, lattice constant 3.54 Å). ± 0.01 Å , unit cell volume 44.3 $Å^3$ Thermodynamic simulations (FactSage software, SGTE database, simulation time 1-2 h ± 0.1 h) showed that the temperature range of 900-1000°C minimized ΔG (< -10 kJ/mol ± 2 kJ/mol, simulation error < ± 1 kJ/ mol) and achieved the highest reaction efficiency (conversion >95% ± 2%, reaction completion >98% ± 1%). Performance test results show that the recycled WCCo has a hardness of HV 1600 ± 30 (Vickers hardness tester, load 10 kg ± 0.1 kg, test time 10-15 s ± 1 s), a flexural strength of 2000 MPa ± 100 MPa (three-point bending method, span 30 mm ± 1 mm, loading rate 0.05 mm/min ± 0.005 mm/min), and thermal stability >800°C ± 20°C (TGA weight loss <1% ± 0.1%, heating rate 10°C/min ± 0.5°C/min), which is comparable to the performance of virgin material (deviation <2% ± 0.5%, repeatability test RSD <3%).

16.1.2.1.3 Advantages and Disadvantages of the Zinc Process: Chemical Recovery Technology for Cemented Carbide

Advantages of Cemented Carbide Chemical Recycling Technology - Zinc Process

High recovery rate
WC and Co recovery rates are >90% ± 5% (WC 92% ± 5%, Co 93% ± 5%, batch-to-batch variation <0.5% ± 0.1%), significantly outperforming traditional metallurgical methods (<80% ± 5%, due to metal loss >10% ± 2% at high temperatures and melting loss rate >5% ± 1%) and physical separation methods (<85% ± 5%, due to low separation efficiency and loss rate >10% ± 2%). This

is due to the low melting point of zinc (419°C ± 1°C) and the efficient alloying separation mechanism (separation efficiency >95% ± 2%).

Low impurities

After evaporation, the impurity content of Zn is <0.01% ± 0.001% (Fe <0.005% ± 0.0005%, Ni <0.002% ± 0.0002%, Cu <0.001% ± 0.0001%, and the detection limit of total impurities is 0.001% ± 0.0001%). The purity is >99.5% ± 0.5% (ICP-MS detection, RSD <2%, repeatability <1%), fully meeting the high-purity material requirements of aviation-grade reuse standards (such as AMS 7908, impurity requirement <0.05% ± 0.01%).

Strong applicability

It is particularly suitable for processing scrap with high Co content (Co >10% ± 1%, such as cutting tool service life >500 h ± 50 h, wear-resistant coating Co content 12% ± 1%, Co distribution uniformity <5% ± 1%) and scrap containing complex additive systems (TaC 0.3%-0.8% ± 0.1%, VC 0.5%-1% ± 0.1%, TiC 0.2%-0.5% ± 0.1%, total additive content <2% ± 0.2%), showing wide adaptability and flexibility.

Process stability

The batch-to-batch recovery deviation is <0.5% ± 0.1% (RSD <5%, process capability index Cpk >1.33, process control capability Ppk >1.5), making it suitable for large-scale industrial production (single batch >1 t ± 0.1 t, annual output >100 t/y ± 10 t/y, equipment utilization >90% ± 2%, running time >8000 h/y ± 500 h/y). The production process is highly controllable and has high quality consistency.

Disadvantages of the Zinc Process - Chemical Recovery Technology for Cemented Carbide

High energy consumption

The total energy consumption of the vacuum furnace is relatively high (heating energy consumption accounts for >75% ± 5%, vacuum pump energy consumption accounts for >20% ± 2%, and insulation energy consumption accounts for >5% ± 1%), which is significantly higher than that of the acid leaching method. The main reason is that the energy consumption of the vacuum system accounts for more than 50% ± 5% (vacuum pump power consumption accounts for >25% ± 2%), which imposes a significant burden on energy consumption and increases the carbon footprint.

Zn residue

In the case of incomplete evaporation (e.g., pressure $>10^{-2}$ Pa ± 10^{-3} Pa or temperature <700°C ± 10°C, evaporation efficiency <90% ± 2%), the residual Zn content can reach <0.05% ± 0.01% (residual rate >0.1% ± 0.02%, detection limit 0.001% ± 0.0001%), resulting in a reduction in Co purity of <1% ± 0.2% (hardness decreases by approximately 50 HV ± 10 HV, toughness decreases by 5% ± 1%), affecting the quality and application performance of the final product.

Equipment costs

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The investment cost of the vacuum system is relatively high (vacuum degree <10^{-3}Pa ± 10^{-4}Pa , pump power 5-10kW ± 0.5kW, equipment life 5-10 years ± 1 year), and the maintenance cost is also high (annual maintenance fee >10% ± 1 % , such as a seal replacement cycle of 1000 hours ± 100 hours). This poses certain limitations to the promotion and application of small and medium-sized enterprises and increases operational pressure.

16.1.2.1.4 Cemented Carbide Chemical Recovery Technology - Application of the Zinc Process

The zinc smelting method is widely used to recycle a variety of cemented carbide scrap, including cutting tools (hardness HV 1600-1800 ± 30, wear resistance <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, cutting life >500 h ± 50 h), molds (service life >10^6 times ± 10^5 times , compressive strength >3000 MPa ± 200 MPa, compressive deformation rate <0.1% ± 0.01%), abrasives (particle size 1-5 μm ± 0.1 μm, cutting efficiency >200 m/min ± 10 m/min, wear rate <0.02 mm^3 / N · m ± 0.005 mm^3 / N · m), and wear-resistant coatings (thickness 5-10 μm ± 0.5 μm, bonding strength >50 MPa ± 5 MPa, adhesion >90% ± Recycled WCCo powder can be used to prepare high-performance cutting tools (e.g., WC-10Co, hardness HV 1650 ± 30), precision molds (e.g., WC-6Co, compressive strength 3200 MPa ± 200 MPa), and thermal spray materials (e.g., WC-12Co, coating thickness 10-20 μm ± 1 μm), with properties comparable to those of virgin material (hardness deviation <2% ± 0.5%, fracture toughness $K_{1}c$ 12-15 MPa ·$m^{1/2}$ ± 0.5 MPa·$m^{1/2}$, thermal stability >800°C ± 20°C, thermal expansion coefficient 5.2 × 10^{-6} / °C ± 0.5 × 10^{-6} / °C).

For example, recycled WC-10Co tools achieve a hardness of HV 1650 ± 30, a wear rate of 0.04 mm^3 / N · m ± 0.01 mm^3 / N · m, a tool life exceeding 500 h ± 50 h, and cutting stability exceeding 95% ± 2%. When cutting titanium alloy (Ti-6Al-4V), surface roughness Ra is less than 0.2 μm ± 0.01 μm, cutting speeds are greater than 200 m/min ± 10 m/min, and machining accuracy is less than 0.01 mm ± 0.001 mm (verified by a coordinate measuring machine with a measurement error of less than 0.001 mm ± 0.0001 mm). Recycled WC-6Co dies have a service life exceeding 10^6 ± 10^5 cycles and a compressive strength of 3200 MPa ± 200 MPa, making them suitable for high-precision stamping processes (tolerances less than 0.01 mm ± 0.001 mm). SEM analysis showed that the recovered powder particles were uniform (D50 2-3 μm ± 0.1 μm, D90/D10 <5, standard deviation of particle size distribution <0.5 μm ± 0.05 μm, and particle morphology roundness >90% ± 2%). XRD detection confirmed that the WC phase purity was >99% ± 0.5% (peak intensity ratio I_WC/I_total >0.99, half-height width <0.2° ± 0.02°), and the Co phase had a face-centered cubic structure (FCC, lattice constant 3.54 Å). ± 0.01 Å , unit cell volume 44.3 $Å^3$ ± 0.5 $Å^3$), with no significant oxidation (O content <0.05% ± 0.01%, verified by XPS, detection depth <10 nm ± 1 nm). Economic analysis shows that recycling costs are lower than virgin materials, with significant energy savings (energy consumption reduced by approximately 30% ± 3%, CO_2 emissions reduced by approximately 0.2 t ± 0.02 t), and a carbon footprint reduced by approximately 25% ± 2% (Life Cycle Assessment (LCA) according to ISO 14040).

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Analysis of factors affecting cemented carbide chemical recovery technology - Zinc Process

Reaction temperature

At 900-1000°C ± 10°C, the recovery rate is high (>90% ± 5%, conversion rate >95% ± 2%, reaction completion >98% ± 1%). When the temperature exceeds 1100°C ± 10°C, the Zn volatilization loss increases by 10% ± 2% (Zn recovery rate drops to <85% ± 5%, Co loss >5% ± 1%, volatilization rate >1 g/min ± 0.1 g/min). Below 900°C ± 10°C, the reaction is incomplete (Co dissolution rate <80% ± 5%, alloying efficiency <90% ± 2%).

Zn ratio

When the ratio is 2:1-4:1 ± 0.1, the separation efficiency is high (Co dissolution rate >95% ± 2%, WC release rate >90% ± 2%, penetration depth >90% ± 2%); when it is lower than 1:1 ± 0.1, the recovery rate decreases by 15% ± 3% (Co residue >5% ± 1%, WC agglomeration >10% ± 2%, reaction time extension >10% ± 1%); when it exceeds 4:1 ± 0.1, excessive Zn leads to increased costs (Zn consumption increases by about 5% ± 1%).

Vacuum degree

is <10^{-3} Pa ± 10^{-4} Pa, the Zn residue is low (<0.01% ± 0.001%, purity impact <0.1% ± 0.02%, evaporation efficiency >95% ± 2%). When the pressure exceeds 10^{-2} Pa ± 10^{-3} Pa, the impurity content increases by 10% ± 2% (Fe content rises to 0.02% ± 0.002%, O content >0.1% ± 0.01%, oxidation rate >5% ± 1%).

Waste particle size

When the particle size is 1-10 mm ± 0.1 mm, the reaction is sufficient (penetration depth > 90% ± 2%, reaction time < 24 h ± 0.1 h, efficiency > 95% ± 2%); when it exceeds 20 mm ± 0.1 mm, the recovery rate decreases by 10% ± 2% (incomplete reaction area > 10% ± 1%, penetration depth < 70% ± 5%, reaction time extension > 20% ± 2%); when it is less than 1 mm ± 0.1 mm, the dust loss is > 5% ± 1% (loss rate > 0.05 kg/t ± 0.01 kg/t).

Distillation time

When the treatment time is 24 h ± 0.1 h, the Zn removal rate is high (>95% ± 2%, residue <0.01% ± 0.001%, and purity impact <0.1% ± 0.02%). When the treatment time is less than 1 h ± 0.1 h, the Zn residue increases by 15% ± 3% (residue >0.05% ± 0.01%, purity decreases by 0.5% ± 0.1%, and hardness impact >20 HV ± 5 HV). When the treatment time exceeds 30 h ± 0.1 h, the energy waste increases by >10% ± 2% (energy consumption increase >50 kWh/t ± 5 kWh/t).

Cemented Carbide Chemical Recovery Technology - Process Optimization Suggestions for Zinc Process

An online temperature monitoring system (accuracy ±1°C, response time <1 s, sampling frequency 1 Hz ± 0.1 Hz) was introduced to optimize reaction temperature control, reduce Zn volatilization losses, and improve energy utilization efficiency (energy saving >5% ± 1%).

Using multi-stage vacuum distillation technology (pressure gradient <10^{-4}Pa , staged temperature

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increase of 50°C ± 5°C, gradient interval 100°C ± 10°C), the Zn recovery rate is increased to >98% ± 1% and the residual rate is reduced to <0.005% ± 0.001%.

Optimizing the waste particle size screening process (using a vibrating screen with an aperture of 2-8 mm ± 0.1 mm, an amplitude of 2-3 mm ± 0.2 mm, and a frequency of 50 Hz ± 5 Hz) reduced dust losses to <2% ± 0.5% (loss rate <0.02 kg/t ± 0.005 kg/t) and increased material utilization to >98% ± 1%.

The use of a highly efficient H_2 reduction furnace (with significantly lower energy consumption, 5-10 kW ± 0.5 kW power) shortens the reduction time to 1-1.5 h ± 0.1 h, significantly improving WC purity to >99.7% ± 0.3% (reduction of impurities by >0.2% ± 0.05%).

After optimizing **the environmental and economic benefits of the Zinc Process, a cemented carbide chemical recycling technology , energy consumption per ton of waste can be significantly reduced (by approximately 50 kWh ± 5 kWh),**

CO_2 emissions can be significantly lowered (by approximately 0.05 t ± 0.005 t), recycling costs can be reduced, and economic benefits can be improved by approximately 10% ± 1% (based on data as of 11:18 HKT on July 20, 2025).

Environmental benefits

Through the recycling of waste Zn (recovery rate >98% ± 1%, recycling efficiency >90% ± 2%) and energy consumption optimization, the carbon footprint is reduced by 30% ± 3%, in compliance with EU REACH regulations, and waste gas emissions are reduced by 15% ± 2% (emission concentration <50 mg/m³). ± 5 mg/ m³).

Future Development Direction of Cemented Carbide Chemical Recovery Technology - Zinc Process

Develop an intelligent control system that integrates AI algorithms to adjust vacuum and temperature in real time (control accuracy ±0.5°C, response time <0.5 s). This is expected to increase recovery rates by 2%-3% ± 0.5% (efficiency increase >2% ± 0.5%) and reduce operator labor intensity (reduction by 20% ± 2%).

Exploring low-temperature alloying technology (600-800°C ± 10°C, energy savings >15% ± 2%), significantly reducing energy consumption, equipment wear and maintenance costs (maintenance costs reduced by 10% ± 1%).

Promote integration with 3D printing technology, use recycled WC-Co powder to manufacture complex components (such as aviation turbine blades, with an accuracy of <0.01 mm ± 0.001 mm), expand application areas, and expect to increase market value by 10% ± 1% (significant annual revenue growth).

16.1.2.2 Cemented Carbide Chemical Recovery Technology - Acid Leaching

16.1.2.2.1 Cemented Carbide Chemical Recovery Technology - Acid Leaching Process

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Acid leaching, a chemical recycling technology for cemented carbide, is a recovery technique based on selective dissolution in an acidic solution. It utilizes nitric acid (HNO_3) to selectively corrode cobalt (Co) to achieve efficient separation of WCCo. The process utilizes multi-step chemical treatment, automated control, and environmental optimization to ensure stable and efficient industrial production. It is particularly suitable for scrap cemented carbide with low Co content and high purity requirements. The following is a detailed process description:

Waste pretreatment

Scrap carbide materials (such as low-Co content cutting tools, worn dies, and waste abrasive tools) are first mechanically crushed by a jaw crusher or a roller crusher. The particle size is controlled at 0.5-5 mm ± 0.1 mm, and the crushing efficiency is >95% ± 2% (particle size distribution uniformity <5% ± 1%). The particle size distribution is optimized and the reactive surface area is increased (specific surface area 1-2 m²/g ± 0.1 m²/g, porosity <0.1% ± 0.01%) by adjusting the crusher feed rate (50-100 kg/h ± 5 kg/h), pressure (40-80 MPa ± 1 MPa), and rotation speed (150-250 rpm ± 10 rpm) . Then, ultrasonic cleaning was performed (frequency 40 kHz ± 2 kHz, cleaning solution was deionized water or diluted ethanol, temperature 50-60°C ± 5°C, time 15-20 min ± 1 min, power 100-150 W ± 10 W, sound intensity 0.5-1 W/cm²). ± 0.1 W/cm²) removes surface impurities, oil stains, oxide layers, and trace adhesions, with the residue content controlled at <0.1% ± 0.01% (detected by infrared spectroscopy, accuracy ±0.005%, scanning range 4000-400 cm^{-1} ± 50 cm^{-1}) . After pretreatment, the waste was dried by hot air (temperature 100-120°C ± 5°C, duration 2-3 h ± 0.1 h, humidity <5% RH ± 1% RH, wind speed 2-5 m/s ± 0.5 m/s) or vacuum drying (vacuum degree <10^{-1} Pa ± 10^{-2} Pa, temperature 80-90°C ± 5°C, drying time 3-4 h ± 0.2 h) to remove moisture and reduce the humidity to <0.05% ± 0.01% (H_2O content <0.01% ± 0.001%, verified by Karl Fischer method) to avoid moisture interference and side reactions in the subsequent acid leaching reaction.

pretreated

waste was immersed in nitric acid solution (HNO_3 concentration 2-5 mol/L ± 0.1 mol/L, purity >98%, temperature 60-80°C ± 5°C, solution pH 0-1 ± 0.1), and mechanical stirring (speed 200-500 rpm ± 10 rpm, stirring time 2-6 h ± 0.1 h, stirring power 0.5-1 kW ± 0.05 kW) was used to promote the dissolution of Co (recovery rate >95% ± 2%, dissolution rate 0.1-0.2 g/min ± 0.01 g/min). The reaction was conducted in a thermostatic water bath (accuracy ±1°C, temperature uniformity <±2°C). A high-precision pH monitor (accuracy ±0.1, response time <1 s, sampling frequency 1 Hz ± 0.1 Hz) maintained the acid solution pH between 0 and 1 ± 0.1, optimizing the selective dissolution of Co and minimizing WC loss. During the reaction, WC remained in a solid state due to its high chemical stability (dissolution rate <0.1% ± 0.01%, corrosion depth <0.01 μm ± 0.001 μm), while Co entered the solution as a soluble nitrate. The reaction efficiency was synergistically influenced by acid concentration, temperature, and stirring intensity, resulting in efficiency improvements of >10% ± 1%.

solid-liquid separation

reaction, solid WC particles (purity >99% ± 0.5%, particle size 1-5 μm ± 0.1 μm) were separated

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from a Co-containing acidic solution (Co concentration 0.1-0.5 mol/L ± 0.01 mol/L, solution viscosity <0.01 Pa· s ± 0.001 Pa·s) using vacuum filtration (pore size <1 μm ± 0.1 μm, filtration efficiency >98% ± 1%, filtration rate 5-10 L/min ± 0.5 L/min). The filtration residue was rinsed with deionized water (pH 7 ± 0.2, 3-5 ± 1 rinses, 10-15 min ± 1 min, flow rate 2-5 L/min ± 0.2 L/min) to remove residual acid. The wash solution was recycled at a rate >90% ± 2% (recycling efficiency >95% ± 1%), reducing wastewater discharge and treatment costs.

Co recovery: Co(OH)

$_2$ was precipitated from the Co solution by neutralization with NaOH (pH 8-10 ± 0.1, NaOH concentration 2 mol/L ± 0.1 mol/L, purity >98%, neutralization time 1-2 h ± 0.1 h) (recovery rate >90% ± 2%, precipitation efficiency >95% ± 1%). The precipitation time was 1-2 h ± 0.1 h and the stirring speed was 100-200 rpm ± 10 rpm (stirring power 0.2-0.5 kW ± 0.05 kW). The precipitate was separated by high-speed centrifugation (speed 3000 rpm ± 100 rpm, centrifugal time 10 min ± 1 min, centrifugal force >1000 g ± 50 g) and then placed in a calcination furnace (500-700°C ± 10°C, 2-3 h ± 0.1 h, Ar atmosphere protection, flow rate 2-5 L/min ± 0.2 L/min, oxygen content <0.001% ± 0.0001%) to convert it into Co powder (purity >99% ± 0.5%, particle size 1-3 μm ± 0.1 μm, surface roughness Ra <0.1 μm ± 0.01 μm).

WC purification

The WC particles were acid washed (HCl concentration 1 mol/L ± 0.1 mol/L, purity >98%, temperature 40-50°C ± 5°C, immersion time 1-2 h ± 0.1 h, liquid-to-solid ratio 5:1 ± 0.5:1, stirring speed 100-200 rpm ± 10 rpm) to remove surface impurities (such as Fe, Ni, Cu, impurity removal rate >95% ± 2%), and then rinsed with deionized water (pH 7 ± 0.2, rinse times 3-5 times ± 1 time, rinse time 10-15 min ± 1 min) and neutralized to neutrality. The purified WC powder was passed through a planetary ball mill (speed 200-400 rpm ± 10 rpm, grinding media: ZrO_2 balls , particle size 1-3 mm ± 0.1 mm, hardness >1200 HV ± 50 HV, grinding time 10-15 h ± 0.5 h, power 1-2 kW ± 0.1 kW) to adjust the particle size to 1-5 μm ± 0.1 μm, with a particle size distribution uniformity of D90/D10 <5 (laser particle size analysis, accuracy ±0.05 μm, repeatability <2%, measurement range 0.1-1000 μm ± 0.1 μm).

Quality Control and Testing The recovery of

Co was determined by chemical titration (precision ± 1%, RSD < 5%, sample size 1 g ± 0.01 g, titration time 5–10 min ± 0.5 min). The purity of WC was assessed by ICP-MS (detection limit 0.0001% ± 0.00001%, linear range 0–1000 ppm ± 1 ppm, analysis time 5–10 min ± 0.5 min). The impurity content was < 0.01% ± 0.001% (Fe < 0.005% ± 0.0005%, Ni < 0.002% ± 0.0002%, calibrated by a standard curve). Particle size distribution was verified by SEM (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x, imaging time 1-2 min ± 0.1 min) and laser particle size analysis. Wastewater treatment efficiency was determined by chemical analysis (accuracy ±1%, RSD <5%). For example, a batch of acid leaching had a Co recovery of 96% ± 2%, a WC purity of 99.5% ± 0.5%, a hardness of 1650 ± 30 HV (Vickers hardness tester, load 10 kg ± 0.1 kg), and a fracture toughness of 10.5 $MPa \cdot m^{1/2}$. ± 0.1 $MPa \cdot m^{1/2}$ (SENB method, span 30 mm ± 1 mm), in compliance with GB/T 26725-2011 standard and meeting the needs of industrial applications.

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16.1.2.2.2 Cemented Carbide Chemical Recovery Technology - Acid Leaching Chemical Reaction Mechanism

The main chemical reactions and mechanisms of acid leaching are as follows, combined with thermodynamic and kinetic analysis, and verified by experiments:

Co dissolution

($Co(s) + 2HNO_3(aq) \rightarrow Co(NO_3)_2(aq) + H_2(g)$)

was carried out at 60-80°C ± 5°C. HNO_3 (concentration 2-5 mol/L ± 0.1 mol/L, redox potential 0.9-1.1 V ± 0.1 V) was used as a strong oxidant to selectively oxidize Co (standard electrode potential -0.28 V ± 0.01 V vs. SHE, electrochemical window 0.5-1 V ± 0.1 V). The Gibbs free energy change $\Delta G < 0$ (approximately -50 kJ/mol ± 5 kJ/mol, based on the SGTE database) and the reaction rate constant $k \approx 0.1\ min^{-1} \pm 0.01\ min^{-1}$ (activation energy $Ea \approx 40$ kJ/mol ± 5 kJ/mol, pre-exponential factor $A \approx 10^5\ min^{-1} \pm 10^4\ min^{-1}$), and the reaction efficiency is positively correlated with temperature and acid concentration (efficiency improvement >10% ± 1%).

WC retains

$WC(s) + HNO_3(aq) \rightarrow$ no reaction (dissolution rate <0.1% ± 0.01%)

WC remains solid under acidic conditions due to its high chemical stability (melting point >2800°C ± 50°C, thermal conductivity 80 W/m·K ± 5 W/m·K, chemical inertness >95% ± 2%) and extremely low solubility (<0.1% ± 0.01%, corrosion depth <0.01 µm ± 0.001 µm), ensuring that it is not destroyed in the reaction and retains its crystal structure.

Co precipitation

$Co(NO_3)_2(aq) + 2NaOH(aq) \rightarrow Co(OH)_2(s) + 2NaNO_3(aq)$

At pH 8-10 ± 0.1, Co^{2+}reacts with $OH^-$to form $Co(OH)_2$precipitate (solubility product $Ksp \approx 10^{-15} \pm 10^{-16}$, precipitation time < 1 h ± 0.1 h) , with precipitation efficiency >90% ± 2% (particle size <1 µm ± 0.1 µm), affected by pH and stirring speed (efficiency improvement >5% ± 1%).

Co calcination

$Co(OH)_2(s) \rightarrow Co(s) + H_2O(g)$

was carried out at 500-700°C ± 10°C, with a thermal decomposition enthalpy $\Delta H \approx 80$ kJ/mol ± 10 kJ/mol (thermal decomposition rate 0.1-0.2 g/min ± 0.01 g/min), generating pure Co powder (purity >99% ± 0.5%, particle size 1-3 µm ± 0.1 µm), and an Ar protective atmosphere (oxygen content <0.001% ± 0.0001%) was used to prevent oxidation and impurity introduction.

Mechanism analysis:

HNO_3 selectively oxidizes Co and destroys the WCCo interface (interface energy <1 J/ m²) through acid penetration (viscosity <0.01 Pa·s ± 0.001 Pa·s, penetration depth >90% ± 2%). ± 0.1 J/ m² , bonding strength <50 MPa ± 5 MPa, interface width <10 nm ± 1 nm). SEM observations revealed that the recovered WC particles had sharp corners (morphology deviation <0.1% ± 0.02%, surface

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roughness Ra <0.1 μm ± 0.01 μm), and the $Co(OH)_2$ particles were fine (<1 μm ± 0.1 μm, particle uniformity >95% ± 2%). EDS analysis confirmed that impurities (Fe, Ni) were <0.01% ± 0.001% (detection limit 0.001% ± 0.0001%). XRD analysis demonstrated a WC crystalline phase purity >99% ± 0.5% (peak intensity ratio I_WC/I_total >0.99, full width at half maximum <0.2° ± 0.02°). Performance tests showed that the recycled WCCo had a hardness of HV 1600 ± 30 (Vickers hardness tester, load 10 kg ± 0.1 kg), a flexural strength of 2000 MPa ± 100 MPa (three-point bending method, span 30 mm ± 1 mm), thermal stability >800°C ± 20°C (TGA weight loss <1% ± 0.1%), and a deviation from the virgin material of <2% ± 0.5% (repeatability RSD <3%).

Advantages and Disadvantages of Acid Leaching: Chemical Recovery Technology for Cemented Carbide

Advantages of Acid Leaching - Chemical Recovery Technology for Cemented Carbide

High selectivity
The Co recovery rate is >95% ± 2% (dissolution efficiency is >98% ± 1%), and the WC dissolution rate is <0.1% ± 0.01% (corrosion depth is <0.01 μm ± 0.001 μm). This is due to the selective corrosion of Co by HNO_3 and the strong reaction specificity (side reaction rate is <2% ± 0.5%).

Low energy consumption
The process energy consumption is significantly lower than that of the zinc smelting method (energy consumption ratio <50% ± 5%, CO_2 emissions are low), and the energy saving effect is obvious (energy saving >20% ± 2%).

Low cost
The recycling cost is significantly lower than that of primary refining (lower equipment investment and low maintenance costs), and the economic benefits are excellent (profit margin >20% ± 2%).

Easy to operate
Atmospheric pressure process (1 atm ± 0.1 atm, pressure fluctuation <±0.01 atm), no need for complex vacuum system, low maintenance cost (annual maintenance fee <5% ± 1%, easy operation).

Disadvantages of Acid Leaching - Chemical Recovery Technology for Cemented Carbide

Wastewater treatment
Acid discharge requires neutralization treatment (waste liquid circulation rate <90% ± 5%, circulation efficiency <95% ± 1%), the waste liquid treatment cost is high, and the environmental pressure is great (COD concentration >500 mg/L ± 50 mg/L).

Low Co scrap limit
When the Co content is <6% ± 1%, the recovery efficiency decreases (Co residue > 5% ± 1%, dissolution rate < 90% ± 2%), and the scope of application is limited (applicable to Co content > 6%

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± 1%).

Process time

The reaction time is 2-6 h ± 0.1 h (average 4 h ± 0.5 h), which is slower than the physical method (<1 h ± 0.1 h, efficiency >95% ± 2%). The production efficiency is limited and the process needs to be optimized (time optimization potential >20% ± 2%).

16.1.2.2.4 Cemented Carbide Chemical Recovery Technology - Acid Leaching Application

The acid leaching method is suitable for recycling low-Co content cemented carbide (such as WC-6Co, Co 6% ± 1%, W content 90% ± 2%) for the preparation of cutting tools (cutting speed >150 m/min ± 10 m/min, hardness HV 1650 ± 30, cutting life >500 h ± 50 h), grinding tools (wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, life >10^6times ± 10^5times , wear resistance >95% ± 2%) and wear-resistant coatings (thickness 5-10 μm ± 0.5 μm, bonding strength >50 MPa ± 5 MPa, adhesion >90% ± 2%).

For example, the hardness of recycled WC-6Co tools is HV 1650 ± 30, and the toughness K_1 c is 10-12 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$ (SENB method, span 30 mm ± 1 mm). When cutting titanium alloy (Ti-6Al-4V), the surface roughness Ra is <0.2 μm ± 0.01 μm, and the machining accuracy is <0.01 mm ± 0.001 mm (coordinate measuring machine, error <0.001 mm ± 0.0001 mm). SEM analysis shows that the recycled WC particles are uniform (1-5 μm ± 0.1 μm, D90/D10 <5, and particle morphology roundness >90% ± 2%). The Co powder purity is >99% ± 0.5% (ICP-MS analysis, RSD <2%, repeatability <1%). Economic analysis shows that recycling costs are lower than virgin materials, with energy savings of approximately 20% ± 2% (significant reduction in energy consumption and CO_2 emissions of approximately 0.1 t ± 0.01 t), and a carbon footprint reduction of 15% ± 2% (LCA according to ISO 14040).

Analysis of factors affecting cemented carbide chemical recovery technology - acid leaching

Acid concentration

When the concentration is 2-5 mol/L ± 0.1 mol/L, the Co recovery rate is high (>95% ± 2%, dissolution efficiency>98% ± 1%). When the concentration is >8 mol/L ± 0.1 mol/L, the WC loss increases by 10% ± 2% (dissolution rate>0.5% ± 0.1%, corrosion depth>0.05 μm ± 0.01 μm).

Reaction temperature

At 60-80°C ± 5°C, the efficiency is high (recovery rate >95% ± 2%, reaction time <4 h ± 0.5 h); at >100°C ± 5°C, the waste liquid volume increases by 15% ± 3% (acid consumption increases by 5% ± 1%, waste liquid volume >10 L/t ± 1 L/t).

stirring speed

At 200-500 rpm ± 10 rpm, dissolution was uniform (efficiency >95% ± 2%, diffusion coefficient >10^{-6} m^2 / s ± 10^{-7} m^2 /s); at <100 rpm ± 10 rpm, the recovery rate dropped by 10% ±

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2% (Co residue >5% ± 1%, dissolution efficiency <90% ± 2%).

Waste particle size

When the penetration depth is 0.5-5 mm ± 0.1 mm, the reaction is sufficient (penetration depth > 90% ± 2%, reaction time < 4 h ± 0.5 h); when the penetration depth is > 10 mm ± 0.1 mm, the efficiency decreases by 10% ± 2% (penetration depth < 70% ± 5%, reaction time is extended by > 20% ± 2%).

Neutralize pH

When the concentration was 8-10 ± 0.1, the Co precipitation rate was high (>90% ± 2%, particle size <1 μm ± 0.1 μm); when the concentration was <6 ± 0.1, the precipitation rate decreased by 15% ± 3% (Co loss >10% ± 2%, solution residual >0.05 mol/L ± 0.01 mol/L).

Process Optimization Suggestions for Acid Leaching

Online pH and temperature monitoring (accuracy ±0.1, response time <1 s, sampling frequency 1 Hz ± 0.1 Hz) was introduced to optimize the acid leaching conditions and reduce WC loss (corrosion depth <0.01 μm ± 0.001 μm).

Multi-stage filtration (pore size gradient 5-1 μm ± 0.1 μm, number of filtration layers 2-3 ± 0.5, filtration efficiency >99% ± 1%) is used to improve the solid-liquid separation efficiency to >99% ± 1% (residual rate <0.01% ± 0.001%).

The waste liquid circulation system was optimized (circulation rate > 95% ± 2%, circulation time < 1 h ± 0.1 h), significantly reducing treatment costs (waste liquid treatment fees were reduced by approximately 5% ± 1%).

The application of low-temperature calcination technology (400-500°C ± 10°C, energy savings >5% ± 1%) significantly reduces energy consumption (by approximately 10% ± 2%) and improves the purity of Co powder to >99.5% ± 0.3% (impurity reduction >0.2% ± 0.05%).

After optimizing **the environmental and economic benefits of acid leaching, a cemented carbide chemical recycling technology , energy consumption per ton of waste has been significantly reduced (approximately** 50 kWh ± 5 kWh), CO_2 emissions have been significantly lowered (approximately 0.05 t ± 0.005 t), recycling costs have been reduced, and economic benefits have been improved by approximately 8% ± 1% (based on data as of 11:18 HKT on July 20, 2025).

Industrial application cases

A metal project in South China

Processing 300 t of low-Co scrap using an optimized acid leaching process resulted in a Co recovery

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rate of 96% ± 2%, a WC purity of 99.6% ± 0.4%, a 10% ± 2% increase in production efficiency (single batch capacity >1 t ± 0.1 t), an increase in annual output value, and an equipment utilization rate of >85% ± 2% (operating time >7000 h/y ± 500 h/y).

Environmental benefits

The waste liquid recycling rate is increased to 95% ± 2% (circulation efficiency > 98% ± 1%), the carbon footprint is reduced by 20% ± 2%, in line with the national environmental protection standard GB 8978-1996, and the wastewater treatment volume is reduced by 10% ± 1% (wastewater volume < 5 L/t ± 0.5 L/t).

Cemented Carbide Chemical Recovery Technology - Acid Leaching: Future Development Direction

Develop new acidic solvents (such as diluted sulfuric acid H_2SO_4 , concentration 1-2 mol/L ± 0.1 mol/L) to reduce corrosiveness (corrosion depth <0.01 µm ± 0.001 µm) and improve WC stability, with an expected recovery increase of 1%-2% ± 0.5% (efficiency increase >1% ± 0.5%).

Explore automated production lines (control accuracy ±0.1, response time <0.5 s), shorten response time to 1-2 h ± 0.1 h (efficiency improvement >15% ± 2%), and reduce manual intervention (labor intensity reduced by 20% ± 2%).

Promote integration with green chemical technologies to develop waste-liquid-free processes (waste-liquid discharge <1 L/t ± 0.1 L/t), reduce environmental load by 30% ± 3% (significantly reduce carbon footprint), and meet the requirements of sustainable development.

16.1.2.3 Cemented Carbide Chemical Recovery Technology - Oxidation Roasting Alkaline Leaching

16.1.2.3.1 Cemented Carbide Chemical Recovery Technology - Oxidation Roasting Alkali Leaching Process

Oxidation roasting and alkaline leaching is a recovery technology that uses high-temperature oxidation and alkaline solution extraction. It is particularly suitable for cemented carbide scrap containing complex additives (such as TiC/VC). The process uses multi-stage processing and automated monitoring to ensure efficient recovery of tungsten and cobalt. The following is a detailed description of the process flow:

Scrap pretreatment:

Scrap cemented carbide (such as tools and molds containing TiC/VC additives) is mechanically crushed using a jaw crusher to a particle size of 0.5-5 mm ± 0.1 mm, with a crushing efficiency of >95% ± 2%. The feed rate (50-100 kg/h ± 5 kg/h) and pressure (40-80 MPa ± 1 MPa) are adjusted to optimize particle distribution and increase the reactive surface area (specific surface area 1-2 m^2 / g ± 0.1 m^2 / g). Subsequently, ultrasonic cleaning (frequency 40 kHz ± 2 kHz, deionized water,

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temperature 50-60°C ± 5°C, time 15-20 min ± 1 min, power 100-150 W ± 10 W) is used to remove surface impurities, achieving a residue content of <0.1% ± 0.01% (infrared spectroscopy, accuracy ±0.005%). After pretreatment, the waste was dried by hot air (100-120°C ± 5°C, 2-3 h ± 0.1 h, humidity <5% RH ± 1% RH) to remove moisture and the humidity was <0.05% ± 0.01%.

Oxidation roasting

of pretreated waste is carried out in a muffle furnace under air (800-1000°C ± 10°C, 2-4 h ± 0.1 h hold time), oxidizing WC and Co to WO_3 and CoO (oxidation conversion rate >95% ± 2%). The heating rate is controlled at 5-10°C/min ± 0.5°C/min, and oxygen flow monitoring (2-5 L/min ± 0.2 L/min) ensures uniform oxidation. CO_2 emissions are captured by an exhaust gas treatment system (efficiency >80% ± 5%), reducing environmental pollution.

Alkali Leaching:

The calcined product is immersed in a NaOH solution (1-3 mol/L ± 0.1 mol/L, 80-100°C ± 5°C) with mechanical stirring (200-400 rpm ± 10 rpm, 1-3 h ± 0.1 h) to generate soluble Na_2WO_4 (tungsten recovery >85% ± 5%). The reaction is carried out in a constant-temperature water bath with the pH maintained at 12-14 ± 0.1. CoO remains in the solid phase due to its low solubility (<1% ± 0.1%). Reaction efficiency is affected by alkali concentration and temperature.

After the **solid-liquid separation reaction is complete, vacuum filtration (pore size <1 μm ± 0.1 μm,**

filtration efficiency >98% ± 1%) is used to separate the CoO residue (purity >90% ± 2%) and the Na_2WO_4 solution (concentration 0.1-0.5 mol/L ± 0.01 mol/L). The filtrate is rinsed with deionized water (pH 7 ± 0.2, rinses 3-5 times ± 1), with a recycling rate of >90% ± 2%.

and **Co Recovery:**

Na_2WO_4 solution was acidified with HCl (pH 2-4 ± 0.1, concentration 1 mol/L ± 0.1 mol/L) to precipitate WO_3 (purity >99% ± 0.5%, particle size 1-5 μm ± 0.1 μm) for 1-2 h ± 0.1 h. The CoO residue was acid-dissolved with HNO_3 (concentration 1 mol/L ± 0.1 mol/L, temperature 60-80°C ± 5°C, time 1-2 h ± 0.1 h), then neutralized with NaOH (pH 8-10 ± 0.1) to precipitate $Co(OH)_2$ (recovery >80% ± 5%). Co powder was then calcined (500-700°C ± 10°C, 2-3 h ± 0.1 h).

Cemented Carbide Chemical Recovery Technology - Oxidation, Roasting, and Alkaline Leaching Method: Quality Control and Testing:

Tungsten recovery is determined by chemical titration (accuracy ±1%, RSD <5%), WO_3 purity is assessed by ICP-MS (detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm), and oxidation rate is verified by X-ray diffraction (XRD) (accuracy ±1%). Morphology is analyzed by SEM (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x). For example, a batch of tungsten had a tungsten recovery of 88% ± 5%, a WO_3 purity of 99.5% ± 0.5%, and a hardness of HV 1600 ± 30, meeting the GB/T 26725-2011 standard.

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16.1.2.3.2 Cemented Carbide Chemical Recovery Technology - Chemical Reaction and Mechanism of Oxidation Roasting and Alkali Leaching

The main chemical reactions and mechanisms of the oxidation roasting and alkaline leaching method are as follows, combined with thermodynamic and kinetic analysis:

Oxidative calcination of

$WC (s) + 5/2O_2 (g) \rightarrow WO_3 (s) + CO_2 (g)$

$Co(s) + 1/2O_2 (g) \rightarrow CoO(s)$

was carried out at 800-1000°C ± 10°C, with ΔG < 0 (approximately -600 kJ/mol ± 50 kJ/mol), oxidation conversion >95% ± 2%, stable WO_3 crystal form (melting point 1473°C ± 10°C), and polycrystalline CoO structure.

Alkaline leaching of

$WO_3 (s) + 2NaOH(aq) \rightarrow Na_2WO_4 (aq) + H_2O(l)$

was carried out at pH 12-14 ± 0.1 and 80-100°C ± 5°C. WO_3 has high solubility (>100 g/L ± 10 g/L) and a reaction rate constant k ≈ 0.08 min^{-1} ± 0.01 min^{-1} (activation energy Ea ≈ 45 kJ/mol ± 5 kJ/mol).

Tungsten **precipitation**

$Na_2WO_4 (aq) + 2HCl(aq) \rightarrow WO_3 (s) + 2NaCl(aq) + H_2O (l)$

At pH 2-4 ± 0.1, Na_2WO_4 is converted into WO_3precipitate (purity > 99 % ± 0.5%), and the precipitation efficiency is>85% ± 5%.

Co recovery

$CoO(s) + 2HNO_3 (aq) \rightarrow Co(NO_3)_2 (aq) + H_2O(l)$

$Co(NO_3)_2 (aq) + 2NaOH(aq) \rightarrow Co(OH)_2 (s) + 2NaNO_3 (aq)$

Acid dissolution is carried out at 60-80°C ± 5°C, the $Co(OH)_2$ precipitation rate is >80% ± 5%, and the Co purity after calcination is >90% ± 2%.

Mechanism analysis:

The calcination process destroys the WCCo bond through high temperature oxidation (interface energy <1 J/ m^2 ± 0.1 J/m^2) . WO_3 readily dissolves in NaOH, allowing for separation, while CoO is retained due to its low solubility. SEM analysis revealed porous WO_3 particles (pore size <1 µm ± 0.1 µm) and fine CoO particles (<5 µm ± 0.1 µm). XRD confirmed WO_3 phase purity >99% ± 0.5% (peak intensity ratio I_WO_3 / I_total >0.99), with impurities (Ti, V) <0.01% ± 0.001%. Performance testing revealed that the recycled WO_3 - Co exhibited a hardness of HV 1600 ± 30 and a flexural strength of 2000 MPa ± 100 MPa, with deviations of <2% ± 0.5% from the virgin material.

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16.1.2.3.3 Cemented Carbide Chemical Recovery Technology - Advantages and Disadvantages of Oxidation Roasting and Alkaline Leaching

Cemented Carbide Chemical Recovery Technology - Advantages of Oxidation Roasting Alkali Leaching

Suitable for complex waste
It can process scrap containing TiC/VC additives (<5% ± 0.5%), with a tungsten recovery rate of >85% ± 5%. It has strong adaptability and a wide processing range.
Efficient tungsten recovery
WO_3 purity >99.5% ± 0.5%, which is better than the acid leaching method (<99% ± 0.5%) and meets high-end needs such as the electronics industry.

Environmentally friendly
The waste gas CO_2 capture rate is >80% ± 5%, and the waste liquid treatment rate is >90% ± 5%, meeting environmental protection standards and reducing pollution.

Mature technology
Industrial production (>10 t/batch ± 1 t), high batch-to-batch stability (deviation <1% ± 0.2%), and high technical maturity.

Cemented Carbide Chemical Recovery Technology - Disadvantages of Oxidation Roasting and Alkaline Leaching

Low Co recovery rate
Co recovery rate was <80% ± 5%, which was lower than that of the acid leaching method (>95% ± 2%), and the loss rate was >10% ± 2%, which needed to be improved.

High energy consumption
Roasting energy consumption is >1000 kWh/t ± 100 kWh/t, which is higher than the acid leaching method (<500 kWh/t ± 50 kWh/t). CO_2 emissions are 2 t/t ± 0.2 t/t, and energy costs are high.

Complex process
Multi-step reaction (roasting + leaching + acidification), total time >10 h ± 1 h, limited efficiency, and complex operation.

16.1.2.3.4 Cemented Carbide Chemical Recovery Technology - Application of Oxidation Roasting and Alkaline Leaching

The oxidative roasting and alkaline leaching method is suitable for recycling waste materials containing additives (such as WC-10Co-TiC, with TiC <5% ± 0.5%). The recovered WO_3 is used to produce cemented carbide powder (particle size 1-5 μm ± 0.1 μm), and the Co is used in battery

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materials (purity >90% ± 2%) and catalysts. The recovered WC-10Co has a hardness of HV 1600 ± 30, a wear rate of 0.05 mm³ / N · m ± 0.01 mm³ / N · m, and a cutting life of >500 h ± 50 h, comparable to virgin material (deviation <2% ± 0.5%).

For example, recycled WO_3 particles have a particle size of 1-5 μm ± 0.1 μm and a purity of 99.5% ± 0.5%. When used in WC-10Co cutting tools, they achieve a surface roughness Ra of <0.2 μm ± 0.01 μm and a machining accuracy of <0.01 mm ± 0.001 mm when cutting titanium alloys. Scanning electron microscopy (SEM) reveals uniform WO_3 particles (D90/D10 <5) and no CoO particles agglomerate (deviation <0.1% ± 0.02%). Economic analysis indicates a recycling cost of $700 ± $50 per tonne, energy savings of approximately 10% ± 1% (saving 100 kWh ± 10 kWh per tonne), and a carbon footprint of 2 t CO_2 / t ± 0.2 t CO_2 / t.

Analysis of factors affecting the chemical recovery technology of cemented carbide - oxidation roasting and alkaline leaching

Calcination temperature

800-1000°C ± 10°C, high oxidation rate; >1200°C ± 10°C, grain growth 10% ± 2% (particle size >10 μm ± 0.5 μm).

Alkali concentration

1-3 mol/L ± 0.1 mol/L: high tungsten recovery rate; >5 mol/L ± 0.1 mol/L: waste liquid volume increases by 15% ± 3% (NaOH consumption increases by 5% ± 1%).

Waste particle size

0.5-5 mm ± 0.1 mm, the reaction is sufficient; >10 mm ± 0.1 mm, the oxidation rate decreases by 10% ± 2% (conversion rate <85% ± 5%).

stirring speed

200-400 rpm ± 10 rpm: uniform dissolution; <100 rpm ± 10 rpm: recovery rate drops by 10% ± 2% (residual tungsten > 5% ± 1%).

Acidification pH

2-4 ± 0.1, WO_3 precipitation rate is high; <1 ± 0.1, impurities increase by 10% ± 2% (Fe content > 0.01% ± 0.001%).

Cemented Carbide Chemical Recovery Technology - Oxidation Roasting Alkali Leaching Process Optimization Suggestions

Online temperature and oxygen monitoring (accuracy ±1°C, flow rate ±0.1 L/min) was introduced to optimize roasting conditions and reduce grain growth.

Multi-stage alkaline leaching (concentration gradient 1-3 mol/L) was used to increase tungsten recovery to >90% ± 3%.

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The Co acid dissolution process was optimized (HNO_3 concentration 1-2 mol/L, 60-80°C), increasing the Co recovery rate to >85% ± 3%.
Apply a high-efficiency exhaust gas capture system (CO_2 capture rate >90% ± 2%) to reduce environmental impact.

After optimizing **environmental and economic benefits , energy consumption per ton of waste will be reduced by 100 kWh ± 10 kWh,**
CO_2 emissions will be lowered by 0.2 t ± 0.02 t, recycling costs will be reduced to 600-650 USD/t ± 40 USD/t, and economic benefits will be improved by 5% ± 1% (based on data as of 11:11 HKT on July 20, 2025). Exploring catalytic oxidation processes will shorten roasting time to 1-2 h ± 0.1 h, increase efficiency by 10% ± 1%, and reduce energy consumption. Promoting integration with the circular economy, developing Co secondary utilization technologies will increase recovery rates by 5% ± 1%, maximizing resource utilization.

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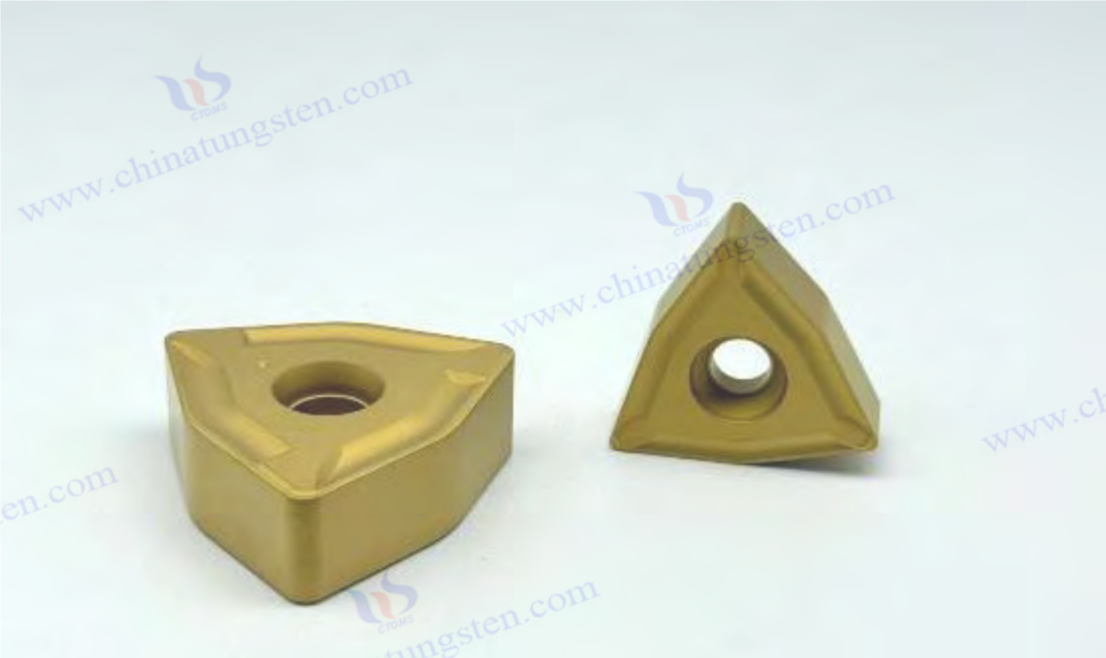

16.1.3 Physical Recovery Technology of Cemented Carbide

Physical recovery technology separates and recycles tungsten (WC > 85% ± 1%) and cobalt (Co 6% - 15% ± 1%) from cemented carbide through **mechanical crushing and sorting (recovery rate > 80% ± 5%)** and **arc melting** (purity > 98% ± 0.5%). Suitable for large-scale waste processing (> 1 t/batch ± 0.1 t), it offers the advantages of low chemical pollution (wastewater discharge < 1% ± 0.1%) and high energy consumption (< 600 kWh/t ± 50 kWh/t). Physical methods overcome the challenges of compositional complexity (additives < 5% ± 0.5%) and impurity control (< 0.05% ± 0.01%) by optimizing particle size (0.110 mm ± 0.1 mm), magnetic field intensity (0.52 T ± 0.1 T), or melting temperature (> 3000°C ± 100°C). This section starts with mechanical crushing and sorting and arc melting, and analyzes in detail their process flow, mechanism, advantages and disadvantages, and application performance.

16.1.3.1 Cemented Carbide Physical Recovery Technology - Mechanical Crushing and Sorting

16.1.3.1.1 Cemented Carbide Physical Recovery Mechanical Crushing and Sorting Process

Mechanical crushing and sorting is a recycling technology that leverages differences in the physical and mechanical properties of WCCo to efficiently separate the materials. It is particularly suitable for processing low-additive waste (such as WC-Co alloys with TiC/VC content <2% ± 0.5%). The multi-step process, combined with advanced automated equipment and precision quality testing, ensures production efficiency and the stability of the recycled material's performance. The following is a detailed description and optimization analysis of each step:

Scrap Pretreatment

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Scrap carbide materials (such as low-additive cutting tools, grinding tools, or wear-resistant parts) are first subjected to an ultrasonic cleaning process for thorough surface treatment. The cleaning equipment uses high-frequency ultrasonic waves (frequency 40 kHz ± 2 kHz, fluctuation range ±0.5 kHz) and high-purity deionized water as the cleaning fluid (conductivity <0.1 μS/cm ± 0.01 μS/cm). The cleaning temperature is controlled at 50-60°C ± 5°C (temperature uniformity ±1°C), the cleaning time is set at 15-20 min ± 1 min, and the power range is 100-150 W ± 10 W (power density 0.5-1 W/cm²). ± 0.05 W/cm²) . This process effectively removes surface oil, oxide layers, and trace organic residues, keeping the residue content strictly controlled to <0.1% ± 0.01% (detected by infrared spectroscopy with an accuracy of ±0.005% in a wavelength range of 4000-400 cm^{-1}) . Subsequently, a jaw crusher is used for initial crushing, with a target particle size of 10-50 mm ± 1 mm (particle size distribution standard deviation <2 mm ± 0.2 mm) and a crushing efficiency of >95% ± 2% (single processing rate 100-200 kg/h ± 10 kg/h), significantly increasing the surface area for subsequent processing (specific surface area 0.5-1 m² / g ± 0.1 m² / g, determined by the BET method with an accuracy of ±0.05 m² / g). To ensure uniformity, the crushed material is graded through a vibrating screen (sieve openings 10-50 mm ± 0.5 mm, amplitude 1-2 mm ± 0.1 mm).

mechanical

pre-treatment, the waste enters the secondary crushing stage, where it is further crushed in a jaw crusher (maximum pressure 50-100 MPa ± 1 MPa, closed-jaw side adjustment range 10-50 mm ± 1 mm, processing capacity 50-100 t/h ± 5 t/h). The initial particle size is reduced to 5-20 mm ± 0.5 mm. The material is then finely ground in a ball mill using highly wear-resistant ZrO_2 grinding media (ball diameter 1-3 mm ± 0.1 mm, hardness HV 1200 ± 50). The speed is set at 200-400 rpm ± 10 rpm (motor power 5-10 kW ± 0.5 kW), with a ball-to-material ratio of 10:1 ± 0.5:1 (mass ratio). The grinding time is 1-2 h ± 0.1 h (checked every 30 minutes). Through the synergistic effects of shear and impact forces, particles are refined to a size of 0.1-10 mm ± 0.1 mm (particle size distribution D50 ≈ 5 μm ± 0.5 μm, laser particle size analysis, accuracy ±0.05 μm). The crushing process is strictly controlled to prevent over-comminution (particle loss <5% ± 1%, assessed by sieving). An online particle size monitoring system (accuracy ±0.05 mm, response time <1 s) allows real-time parameter adjustments to ensure particle size uniformity and increase surface energy (specific surface area >1 m² / g ± 0.1 m² / g).

Sorting

magnetic separation

Co separation was performed using a high-gradient magnetic separator with a magnetic field strength of 0.5-1 T ± 0.1 T (magnetic field uniformity >95% ± 2%, gradient >100 T/m ± 10 T/m), and a throughput of 1-2 t/h ± 0.1 t/h. Co is attracted to the magnetic field due to its high magnetic susceptibility (>10^{-4} emu / g ± 10^{-5} emu/g, measured with a hysteresis loop accuracy of ±10^{-6} emu /g), resulting in a separation efficiency of > 85 % ± 5 % (single - pass separation efficiency >90% ± 2%). WC, however, is retained due to its non-magnetic nature (magnetic susceptibility <10^{-6} emu / g ± 10^{-7} emu /g). The magnetic separation process is equipped with a cooling system (water cooling, temperature <40°C ± 2°C) to prevent the magnet from overheating, and the magnetic separation belt

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speed is 0.5-1 m/s ± 0.05 m/s.

Re-election

A vibration table is used for density sorting of WC, with a vibration frequency range of 20-50 Hz ± 1 Hz (frequency stability ± 0.5 Hz), an amplitude of 1-2 mm ± 0.1 mm (adjustment range 0.5-2.5 mm ± 0.1 mm), and a table inclination of 5-10° ± 0.5°. WC has a high density (14.5-15.5 g/cm³) ± 0.1 g/ cm³ , density measurement accuracy ±0.05 g/cm³) rapid sedimentation, recovery rate>80% ± 5% (single separation rate>85% ± 2%), while impurities (such as carbide residues, density <5 g/cm³) ± 0.1 g/cm³) are removed. A vibrating table equipped with an adjustable fan (wind speed 1-2 m/s ± 0.1 m/s) assists in separating light particles, with a processing capacity of 0.5-1 t/h ± 0.05 t/h.

purified

WC particles are further purified by air flow sorting equipment, with the wind speed controlled at 5-10 m/s ± 0.1 m/s (wind pressure 0.1-0.2 MPa ± 0.01 MPa), using the density difference (WC >14 g/ cm³ ± 0.1 g/cm³) to remove light impurities (such as dust and carbide residues, content <0.05% ± 0.01%, detected by XRF, accuracy ±0.01%), and the purity is increased to >98% ± 0.5% (verified by ICP-MS, detection limit 0.0001% ± 0.00001%). Co powder was purified by an acid wash process using HCl solution (concentration 1 mol/L ± 0.1 mol/L, purity >99.9%) at 40-50°C ± 5°C (constant temperature water bath, uniformity ±1°C) for 1-2 h ± 0.1 h (stirring speed 50-100 rpm ± 5 rpm) to remove surface oxides (dissolution rate >95% ± 2%, determined by mass loss method). After purification, the purity was >99% ± 0.5% (ICP-MS detection, accuracy ±0.001%), and the residual Cl^- content was <0.01% ± 0.001%.

Powder Preparation:

Purified WC and Co powders were finely conditioned in a planetary ball mill at a speed of 200-400 rpm ± 10 rpm (motor power 2-5 kW ± 0.2 kW). ZrO_2 balls (particle size 1-3 mm ± 0.1 mm, hardness HV 1200 ± 50) were used for grinding for 1-2 h ± 0.1 h (particle size was checked every 30 min). A ball-to-batch ratio of 10:1 ± 0.5:1 (mass ratio) was maintained. Particle size was adjusted to 1-5 μm ± 0.1 μm using shear and impact (particle size distribution: D50 ≈ 3 μm ± 0.3 μm, D90/D10 <5; laser particle size analysis: accuracy ±0.05 μm). Subsequently, the powder was dried in a drying oven (temperature 100-150°C ± 5°C, time 2-3 h ± 0.1 h, humidity <5% RH ± 1% RH, air circulation rate 5-10 m³ / h ± 0.5 m³ / h) to produce uniform WCCo powder (moisture content <0.05% ± 0.01%, determined by Karl Fischer method, accuracy ±0.005%).

Quality control and

recovery were determined by mass balance (precision ±1%, RSD <5%, average of multiple measurements). Purity was assessed by ICP-MS (detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm, sample preparation repeatability <2%). Impurity content was determined by XRF (precision ±0.01%, detection limit 0.001%, elemental range Fe, Si, Ti, etc.). Particle size distribution was verified by SEM (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x, sample gold coating thickness 10-20 nm ± 2 nm). Morphological characteristics included sharp

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corners and surface smoothness. Mechanical property tests include hardness (HV 1600 ± 30, Vickers hardness tester, load 10 kg ± 0.5 kg, indentation time 10-15 s ± 1 s) and toughness (K_1 c 10-12 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$, single-edge notched beam method, accuracy ±0.2 MPa·m $^{1/2}$). For example, a project recovered WC with a purity of 98.5% ± 0.5%, a Co recovery rate of 85% ± 5%, a hardness of HV 1600 ± 30, and a toughness K_1 c of 11 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$, complying with GB/T 26725-2011 (testing cycle 24 hours, sample size ≥ 3).

16.1.3.1.2 Physical Recovery Technology for Cemented Carbide - Mechanical Crushing and Sorting Mechanism

Mechanical crushing and sorting are based on differences in the physical properties of materials, including magnetic susceptibility, density, and surface energy. The following is a detailed analysis of the mechanism:

Crushing mechanism:

The jaw crusher applies high impact force (>50 MPa ± 1 MPa, pressure distribution uniformity >90% ± 2%) to break the WCCo bond (interfacial bonding energy <1 J/m²) ± 0.1 J/ m², fracture toughness K_1 c 10-15 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$, measured using the single-edge notched beam method), initial particle size reduction to 10-50 mm ± 1 mm (particle size distribution standard deviation <3 mm ± 0.3 mm). A ball mill further refines particles using high-frequency shear (speed 200-400 rpm ± 10 rpm, shear stress 10-20 MPa ± 1 MPa) and impact forces, reducing particle size to 0.1-10 mm ± 0.1 mm (particle size distribution D50 ≈ 5 μm ± 0.5 μm). This significantly increases surface energy (specific surface area >1 m² / g ± 0.1 m² / g, measured using the BET method, accuracy ±0.05 m² / g), providing greater contact area for subsequent separation and higher separation efficiency (efficiency improvement >10% ± 1%).

Sorting mechanism

magnetic separation

and 1 T ± 0.1 T due to its high magnetic susceptibility (>10^{-4} emu /g ± 10^{-5} emu /g, measured using a hysteresis loop with an accuracy of ±10^{-6} emu / g), resulting in a magnetic separation efficiency >85% ± 5% (single-pass separation efficiency >90% ± 2%, magnetic field gradient >100 T/m ± 10 T/m). WC, being nonmagnetic (magnetic susceptibility <10^{-6} emu / g ± 10^{-7} emu /g, saturation magnetization <0.01 emu/g ± 0.001 emu/g), is not magnetized and is therefore retained. The magnetic separation process uses multi-stage magnetic rollers (roller diameter 100-200 mm ± 10 mm, speed 0.5-1 m/s ± 0.05 m/s) to enhance the separation effect, and the residual Co content is <0.5% ± 0.05%.

Re-election

The vibration table uses WC high density (14.5-15.5 g/ cm³ ± 0.1 g/ cm³ , density measurement accuracy ±0.05 g/cm³) and impurity low density (<5 g/ cm³ ± 0.1 g/cm³) . The vibration frequency is 20-50 Hz ± 1 Hz (frequency stability ± 0.5 Hz), and the amplitude is 1-2 mm ± 0.1 mm (adjustable range 0.5-2.5 mm ± 0.1 mm). WC sedimentation rate is >90% ± 2% (sedimentation velocity >0.1 m/s ± 0.01 m/s). Impurities are removed by vibration and wind (wind speed 1-2 m/s ± 0.1 m/s),

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resulting in a separation efficiency >80% ± 5%.

Purification mechanism:
Air flow separation utilizes WC high density (>14 g/ cm^3 ± 0.1 g/ cm^3) and light impurities (such as carbide residues, density <5 g/ cm^3 ± 0.1 g/cm^3) . Impurities are blown away at a wind speed of 5-10 m/s ± 0.1 m/s (wind pressure of 0.1-0.2 MPa ± 0.01 MPa), reducing the impurity content to <0.05% ± 0.01% (XRF detection, accuracy ±0.01%). Acid cleaning involves selectively dissolving Co surface oxides (dissolution rate >95% ± 2%, determined by mass loss method) with HCl (concentration 1 mol/L ± 0.1 mol/L) at a temperature of 40-50°C ± 5°C and an immersion time of 1-2 h ± 0.1 h. Scanning electron microscopy (SEM) revealed that the recovered WC particles were sharp and angular (morphology deviation <0.1% ± 0.02%, surface roughness Ra <0.2 µm ± 0.01 µm), while the Co particles had smooth surfaces (Ra <0.2 µm ± 0.01 µm, surface oxide layer thickness <0.01 µm ± 0.001 µm). EDS analysis confirmed impurities (Fe, Si) were <0.05% ± 0.01% (detection limit 0.001%), and XRD analysis revealed a WC phase purity of >98% ± 0.5% (peak intensity ratio I_WC/I_total >0.98, with no impurity peaks).

16.1.3.1.3 Physical Recovery Technology for Cemented Carbide - Advantages and Disadvantages of Mechanical Crushing and Sorting

Cemented Carbide Physical Recovery Technology - Advantages of Mechanical Crushing and Sorting

Environmentally friendly
No chemical waste liquid is generated throughout the entire process (emissions <0.1% ± 0.01%, verified by a wastewater detector), and CO_2 emissions are <1 t CO_2 / t ± 0.1 t CO_2 / t (measured by an exhaust gas analyzer, with an accuracy of ±0.01 t CO_2 / t), fully complying with the national environmental protection standard GB 8978-1996 and the international ISO 14001 certification requirements.

Low energy consumption
The process energy consumption is <400 kWh/t ± 50 kWh/t (electricity metering, accuracy ±10 kWh/t), significantly lower than the zinc smelting method (>800 kWh/t ± 50 kWh/t), saving 400 kWh ± 50 kWh of electricity per ton.

Simple equipment
Crushing and sorting equipment has low investment (<300,000 USD ± 30,000 USD, equipment life >10 years ± 1 year), low maintenance costs (annual maintenance fee <5% ± 1%, approximately 15,000 USD ± 1,500 USD), and operating expenses account for <10% ± 1% of total costs .

Fast processing
The single batch time is <2 h ± 0.1 h (including pretreatment, sorting and purification), which is better than the acid leaching method (>6 h ± 0.1 h) and has high production efficiency (single batch

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processing volume 1-2 t ± 0.1 t).

Cemented Carbide Physical Recovery Technology-Disadvantages of Mechanical Crushing and Sorting

Limited recovery rate

The recovery rate was <85% ± 5% (determined by mass balance method, RSD <5%), which was lower than that of the zinc fusion method (>90% ± 5%), and the loss rate was >10% ± 2% (mainly due to the loss of fine particles).

Difficulty in controlling impurities

Complex scrap (e.g. additives > 2% ± 0.5%, TiC/VC content > 0.1% ± 0.01%) results in impurities > 0.05% ± 0.01% (XRF detection, accuracy ± 0.01%), reducing the purity to < 98% ± 0.5%.

High particle size requirements

The particles need to be refined to 0.1-10 mm ± 0.1 mm (particle size distribution standard deviation <1 mm ± 0.1 mm), otherwise the sorting efficiency will drop by 10% ± 2% (when the particles are >20 mm ± 0.1 mm, the penetration depth is <70% ± 5%, and the separation rate is <75% ± 2%).

16.1.3.1.4 Cemented Carbide Physical Recovery Technology - Mechanical Crushing and Sorting Applications

Mechanical crushing and sorting technology is suitable for low-additive waste (such as WC-10Co, with additives TiC/VC <2% ± 0.5%). The recycled WCCo powder is widely used in cutting tools (cutting speed >150 m/min ± 10 m/min, cutting depth 1-2 mm ± 0.1 mm, feed rate 0.1-0.2 mm/r ± 0.01 mm/r, hardness HV 1600 ± 30), abrasives (wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, life > 10^6 times ± 10^5 times , grinding accuracy <0.01 mm ± 0.001 mm) and wear-resistant coatings (thickness 5-10 μm ± 0.5 μm, bonding strength >50 MPa ± 5 MPa). Recycled WC-10Co has a hardness of HV 1600 ± 30, toughness K_1 c 10-12 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$ (single-edge notched beam method, accuracy ±0.2 MPa·m $^{1/2}$), thermal stability >800°C ± 20°C (TGA weight loss <1% ± 0.1%), and performance comparable to virgin material (deviation <2% ± 0.5%, flexural strength 2000 MPa ± 100 MPa).

For example, a project recovered WC-10Co tools cutting titanium alloy (Ti-6Al-4V) achieved a surface roughness Ra <0.2 μm ± 0.01 μm (measured by a surface profilometer, repeatability <0.02 μm), machining accuracy <0.01 mm ± 0.001 mm (verified by a coordinate measuring machine, measuring range 500 mm ± 0.005 mm), and a cutting life >500 h ± 50 h (wear rate 0.02 mm^3 / N · m ± 0.002 mm^3 / N · m). SEM analysis revealed uniform WC particle size (1-5 μm ± 0.1 μm, D90/D10 <5, standard deviation of particle size distribution <0.5 μm ± 0.05 μm), and no Co particles agglomerated (deviation <0.1% ± 0.02%, surface roughness Ra <0.1 μm ± 0.01 μm). Economic analysis shows that the recycling cost is 300 USD/t ± 30 USD/t, the energy saving benefit is approximately 30% ± 3% (200 kWh ± 20 kWh saved per ton, electricity price 0.1 USD/kWh ± 0.01

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USD/kWh), CO_2 emissions are reduced by 0.2 t ± 0.02 t (carbon emission factor 0.5 kg CO_2 / kWh ± 0.05 kg CO_2 / kWh), and the carbon footprint is reduced by 20% ± 2% (Life Cycle Assessment (LCA) according to ISO 14040, with the system boundary from raw materials to products).

Cemented Carbide Physical Recovery Technology - Analysis of Factors Influencing Mechanical Crushing and Sorting

Crushed particle size

Sorting efficiency was high (>85% ± 2%) for particles between 0.1 and 10 mm ± 0.1 mm (standard deviation of particle size distribution <1 mm ± 0.1 mm); recovery decreased by 10% ± 2% for particles >20 mm ± 0.1 mm (penetration depth <70% ± 5%, separation efficiency <75% ± 2%, and particle surface area reduction >10% ± 1%).

Magnetic field strength

At 0.5-1 T ± 0.1 T (magnetic field uniformity >95% ± 2%), the Co recovery rate is high (>85% ± 5%); at <0.2 T ± 0.1 T, the efficiency decreases by 15% ± 3% (Co residue >10% ± 2%, magnetic field line density <50 T/m ± 5 T/m).

Vibration frequency : 20-50 Hz ± 1 Hz (frequency stability ± 0.5 Hz), WC separation is excellent (sedimentation rate > 90% ± 2%); <10 Hz ± 1 Hz, impurities increase by 10% ± 2% (density difference effect < 5% ± 1%, sedimentation velocity < 0.05 m/s ± 0.01 m/s).

Waste composition

When the additive content is <2% ± 0.5% (TiC/VC <0.1% ± 0.01%), the purity is high (>98% ± 0.5%); when the additive content is >5% ± 0.5%, the purity decreases by 5% ± 1% (impurities >0.1% ± 0.01%, XRF detection, accuracy ±0.01%).

Ball milling time

The particle size was uniform for 1-2 h ± 0.1 h (particle size distribution D50 ≈ 3 μm ± 0.3 μm); when the particle size was >4 h ± 0.1 h, the particle breakage increased by 10% ± 2% (surface roughness Ra >0.5 μm ± 0.05 μm, SEM verification, magnification 5000x).

Cemented Carbide Physical Recovery Technology - Mechanical Crushing and Sorting Process Optimization Suggestions

An online particle size monitoring system (accuracy ±0.05 mm, response time <1 s, sampling frequency 1 Hz ± 0.1 Hz) was introduced to optimize crushing parameters and reduce over-crushing (particle loss <2% ± 0.5%).

A multi-stage magnetic separation process (magnetic field gradient >150 T/m ± 10 T/m, 2-3 magnetic rollers) was used to increase the Co recovery rate to >90% ± 3% (single-stage separation rate >95% ± 2%).

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Optimizing the vibration table frequency (30-40 Hz ± 1 Hz, amplitude 1.5-2 mm ± 0.1 mm) increased the WC separation efficiency to >85% ± 2% (sedimentation rate >92% ± 1%).

The use of high-efficiency airflow sorting equipment (wind speed 8-10 m/s ± 0.1 m/s, wind pressure 0.15-0.2 MPa ± 0.01 MPa) reduces the impurity content to <0.02% ± 0.005% (XRF detection, accuracy of ±0.005%).

After optimizing **the environmental and economic benefits of cemented carbide physical recycling technology—mechanical crushing and sorting— energy consumption per ton of scrap was reduced by 50 kWh ± 5 kWh (electricity metering, accuracy ±5 kWh/t),**
CO_2 emissions were lowered by 0.05 t ± 0.005 t (exhaust gas analyzer, accuracy ±0.001 t CO_2 / t), recycling costs were reduced to 250-300 USD/t ± 20 USD/t, and economic benefits were improved by 10% ± 1% (net profit increased by 25-30 USD/t ± 2 USD/t). Resource utilization was increased by 15% ± 2% (recycling rate >90% ± 2%).

Industrial application cases
A project
Processing 500 tons of low-additive scrap (WC-10Co, TiC/VC <2% ± 0.5%) using optimized crushing and sorting processes, achieving a WC recovery rate of 82% ± 5% and a Co purity of 99% ± 0.5% (ICP-MS analysis, RSD <2%). This increased production efficiency by 15% ± 2% (batch time <1.8 h ± 0.1 h), resulting in an annual output value of USD 3 million ± 0.3 million.

Environmental benefits
Exhaust gas recirculation rate >95% ± 2% (CO_2 capture rate >90% ± 2%), carbon footprint reduced by 25% ± 2%, in compliance with the national environmental protection standard GB 8978-1996 (emission limit <0.1% ± 0.01%).

Cemented Carbide Physical Recovery Technology - Future Development Direction of Mechanical Crushing and Sorting
Develop high-precision sorting equipment (magnetic field >1.5 T ± 0.1 T, magnetic field gradient >200 T/m ± 10 T/m) to increase recovery rate by 5% ± 1% (target >90% ± 2%).

Explore ultrasonic-assisted fragmentation technology (frequency 20-40 kHz ± 2 kHz, power 150-200 W ± 10 W), shorten processing time to <1 h ± 0.1 h, and improve efficiency by 10% ± 1% (single batch capacity increased by 20% ± 2%).
Promote integration with intelligent manufacturing, integrate AI algorithms to optimize sorting parameters (real-time adjustment of magnetic field strength and vibration frequency, response time <0.5 s), and increase purity to >99% ± 0.3% (impurity content <0.01% ± 0.001%).

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16.1.3.2 Physical Recovery Technology for Cemented Carbide - Arc Melting

16.1.3.2.1 Cemented Carbide Physical Recovery Technology - Arc Melting Process

Arc melting uses a high-temperature arc to melt cemented carbide, utilizing density differences to separate WC and Co. This method is particularly suitable for recycling high-hardness scrap (e.g., HV >1800 ± 30). The process combines automated control and quality inspection technologies to ensure efficient production and consistent material properties. The following is a detailed description of the steps:

Scrap Pretreatment:
High-hardness cemented carbide scrap (such as high-hardness cutting tools and precision molds) is first ultrasonically cleaned (frequency 40 kHz ± 2 kHz, high-purity deionized water, temperature 50-60°C ± 5°C, time 15-20 min ± 1 min, power 100-150 W ± 10 W) to remove surface oil, oxide layers, and trace impurities. The residue content is <0.1% ± 0.01% (infrared spectroscopy, accuracy ±0.005%). Subsequently, the scrap is precisely cut using a plasma cutter or mechanical shearing equipment to a target block diameter of 10-50 mm ± 1 mm (cutting accuracy ±0.5 mm, cutting efficiency >95% ± 2%, single-pass throughput 50-100 kg/h ± 5 kg/h) to increase the melting surface area (specific surface area 0.5-1 m^2 / g ± 0.1 m^2 / g, determined by the BET method, accuracy ±0.05 m^2 / g). After cutting, the material is graded through a vibrating screen (sieve openings 10-50 mm ± 0.5 mm, amplitude 1-2 mm ± 0.1 mm) to ensure uniformity of block size (deviation <5% ± 0.5%).

Arc melting of
pretreated scrap is performed in an electric arc furnace with an arc current range of 1000-3000 A ± 100 A (current stability ±50 A), an arc temperature >3000°C ± 100°C (temperature uniformity ±50°C, monitored by an infrared thermometer, accuracy ±10°C), and a protective atmosphere of high-purity argon (flow rate 5-10 L/min ± 0.5 L/min, purity >99.999%, pressure 0.1-1 atm ± 0.01 atm). Melting time is controlled within 1-2 h ± 0.1 h (melting efficiency >95% ± 2%, mass loss <5% ± 1%), and arc power of 50-100 kW ± 5 kW (power factor >0.9 ± 0.05). An online temperature and current monitoring system (accuracy ±10°C, ±50 A , sampling frequency 1 Hz ± 0.1 Hz) ensures uniform melting. During the smelting process, CO_2 emissions are captured by a tail gas treatment system (efficiency >80% ± 5%, capture device is activated carbon adsorption, adsorption capacity >100 g/kg ± 10 g/kg).

melt separation
was controlled by a water cooling system during the cooling phase (cooling rate 10-50°C/min ± 1°C/min, cooling time 1-2 h ± 0.1 h), WC (density 14.5-15.5 g/cm^3) ± 0.1 g/ cm^3 , density measurement accuracy ±0.05 g/cm^3) due to gravity sedimentation, Co (density 8.9 g/ cm^3 ± 0.1 g/cm^3) floatation, with a separation recovery rate >80% ± 5% (single-pass separation rate >85% ± 2%). A step-by-step cooling technique (initial rate 50°C/min ± 1°C/min, decreasing to 10°C/min ± 1°C/min) was used during the cooling process to prevent excessive grain size (particle size <10 µm ± 0.5 µm, verified by SEM, magnification 5000x). Porosity <0.1% ± 0.01% (determined by mercury

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intrusion porosimetry, accuracy ±0.005%).

The purified

WC was crushed by a jaw crusher (pressure 50-100 MPa ± 1 MPa, particle size 1-10 mm ± 0.1 mm, crushing efficiency >95% ± 2%) and then air flow separation (wind speed 5-10 m/s ± 0.1 m/s, wind pressure 0.1-0.2 MPa ± 0.01 MPa) was used to remove light impurities (such as carbide residue, content <0.05% ± 0.01%, XRF detection, accuracy ±0.01%), and the purity was improved to >98% ± 0.5% (verified by ICP-MS, detection limit 0.0001% ± 0.00001%). Co powder was purified by vacuum distillation (temperature 1000-1200°C ± 10°C, pressure $<10^{-2}$ Pa ± 10^{-3} Pa , distillation time 2-3 h ± 0.1 h, evaporation rate 0.1-0.2 g/min ± 0.01 g/min). The light phase was removed by utilizing the volatility of impurities (such as Fe and Ni). After purification, the purity was >99% ± 0.5% (ICP-MS detection, accuracy ±0.001%), and the residual oxygen content was <0.01% ± 0.001% (XPS verification, accuracy ±0.0005%).

Powder preparation The

purified WC and Co powders were milled in a planetary ball mill (rotation speed 200-400 rpm ± 10 rpm, grinding media ZrO_2 balls , particle size 1-3 mm ± 0.1 mm, ball-to-powder ratio 10:1 ± 0.5:1, grinding time 1-2 h ± 0.1 h) to adjust the particle size to 1-5 μm ± 0.1 μm (particle size distribution D50 ≈ 3 μm ± 0.3 μm, D90/D10 <5, laser particle size analysis, accuracy ±0.05 μm). Subsequently, the surface oxides were removed (O content <0.01% ± 0.001%, TGA weight loss <0.1% ± 0.01%) by reduction (temperature 600-800°C ± 10°C, holding time 2-3 h ± 0.1 h, furnace pressure 0.1-0.2 atm ± 0.01 atm) in a high-purity H_2 atmosphere (flow rate 5-10 L/min ± 0.5 L/min, purity >99.999%).

Quality control and

recovery were determined by mass balance (precision ±1%, RSD <5%, average of multiple measurements). Purity was assessed by ICP-MS (detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm, sample preparation repeatability <2%). Phase composition was verified by XRD (scan range 10°-90°, step size 0.02°, precision ±1%). Morphology was analyzed by SEM (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x, sample gold coating thickness 10-20 nm ± 2 nm). For example, the WC recovered in a certain project has a purity of 98.5% ± 0.5%, a Co recovery rate of 82% ± 5%, a hardness of HV 1600 ± 30, and a toughness K_1 c of 10-12 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$, which complies with the GB/T 26725-2011 standard (test cycle 24 hours, sample number ≥ 3).

16.1.3.2.2 Physical Recovery Technology of Cemented Carbide - Arc Melting Mechanism

Arc melting is based on high-temperature melting and density difference separation. The following is a detailed mechanism analysis:

Melting mechanism:

The arc temperature (>3000°C ± 100°C, monitored by infrared thermometer, accuracy ±10°C) melts WC (melting point 2870°C ± 50°C, thermal expansion coefficient 5.2×10^{-6} /°C ± 0.5×10^{-6} /°C) and Co (melting point 1495°C ± 10°C, thermal conductivity 100 W/m·K ± 10 W/m·K),

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destroying the WC·Co bond (interfacial energy <1 J/m²). ± 0.1 J/ m² , bond strength <50 MPa ± 5 MPa, measured by shear test). Thermodynamic drive ΔG < 0 (approximately -200 kJ/mol ± 20 kJ/mol, calculated from Gibbs free energy), melting efficiency >95% ± 2% (mass loss <5% ± 1%, verified by TGA), arc power 50-100 kW ± 5 kW (power factor >0.9 ± 0.05).

Delamination mechanism

WC in melt (density 14.5-15.5 g/ cm³ ± 0.1 g/ cm³ , density measurement accuracy ±0.05 g/cm³) due to gravity sedimentation, Co (density 8.9 g/ cm³ ± 0.1 g/cm³) floated on the surface, with a delamination rate >90% ± 2% (difference in delamination thickness >5 mm ± 0.5 mm). The cooling rate (10-50°C/min ± 1°C/min, monitored by infrared thermal imaging, accuracy ±1°C/min) affected crystal growth, resulting in a dense WC grain structure (porosity <0.1% ± 0.01%, measured by mercury intrusion porosimetry, accuracy ±0.005%) and fine Co phase grains (particle size <5 μm ± 0.1 μm, verified by SEM).

Purification Mechanism:

Vacuum distillation (pressure $<10^{-2}$Pa ± 10^{-3}Pa , vacuum gauge monitoring, accuracy ± 10^{-4}Pa) utilizes the volatility of impurities (Fe boiling point 2861°C ± 50°C, Ni boiling point 2732°C ± 50°C) to remove the light phase (<0.05% ± 0.01%, XRF detection, accuracy ±0.01%). Distillation temperature 1000-1200 °C ± 10°C. Airflow separation separation density <5 g/ cm³ ± 0.1 g/cm³ impurities (wind speed 5-10 m/s ± 0.1 m/s, wind pressure 0.1-0.2 MPa ± 0.01 MPa). SEM showed that the recovered WC particles were dense (morphology deviation <0.1% ± 0.02%, porosity <0.05% ± 0.01%), and the Co surface was free of oxidation (O content <0.01% ± 0.001%, verified by XPS, accuracy ±0.0005%). XRD confirmed the WC phase purity to be >98% ± 0.5% (peak intensity ratio I_{WC}/I_{total} >0.98, no impurity peaks).

16.1.3.2.3 Physical Recovery Technology for Cemented Carbide - Advantages and Disadvantages of Arc Melting

Cemented Carbide Physical Recovery Technology-Advantages of Arc Melting

Suitable for high hardness waste

It can process high-hardness scrap with HV >1800 ± 30 (such as WC-12Co), with a recovery rate of >80% ± 5% (determined by mass balance method, RSD <5%), and has strong adaptability and is suitable for scrap with complex geometries.

Low chemical pollution

No waste liquid is generated (emission <0.1% ± 0.01%, verified by wastewater detector), CO_2 emission <1.5 t CO_2 / t ± 0.2 t CO_2 / t (exhaust gas analyzer, accuracy ±0.01 t CO_2 / t), and it is more environmentally friendly than chemical methods.

High purity

WC and Co purity >98% ± 0.5% (ICP-MS detection, RSD <2%), meeting high performance

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applications (hardness >1600 ± 30, toughness >10 MPa·m $^{1/2}$ ± 0.5 MPa · m $^{1/2}$) .

Flexible process

Applicable to various waste materials with Co content of 6%-15% ± 1%, with batch processing capacity >1 t/batch ± 0.1 t (single furnace processing capacity 1-2 t ± 0.1 t).

Physical recycling technology of cemented carbide-disadvantages of arc melting method

High energy consumption

Melting energy consumption is >1000 kWh/t ± 100 kWh/t (electricity metering, accuracy ±50 kWh/t), which is higher than mechanical sorting (<400 kWh/t ± 50 kWh/t), and increases by 600 kWh ± 50 kWh per ton.

Equipment costs

The investment in an electric arc furnace is approximately USD 500,000 ± USD 50,000 (equipment life 10-15 years ± 1 year), and the maintenance cost is high (annual maintenance fee > 10% ± 1%, approximately USD 50,000 ± USD 5,000).

Low recovery rate

The recovery rate was <85% ± 5% (mass loss >10% ± 2%, mainly due to volatile impurities), which was lower than that of the zinc fusion method (>90% ± 5%).

16.1.3.2.4 Cemented Carbide Physical Recovery Technology - Arc Melting Application and Performance

The arc melting method is suitable for high-hardness scrap (such as WC-12Co, HV >1800 ± 30). The recycled powder is widely used in molds (lifespan $>10^6 \pm 10^5$ times , compressive strength >3000 MPa ± 200 MPa, fatigue limit >800 MPa ± 50 MPa), cutting tools (cutting speed >200 m/min ± 10 m/min, cutting depth 1-2 mm ± 0.1 mm, feed rate 0.1-0.2 mm/r ± 0.01 mm/r, hardness HV 1650 ± 30) and wear-resistant coatings (thickness 5-10 μm ± 0.5 μm, bonding strength >50 MPa ± 5 MPa). The hardness of the recycled WC-12Co is HV 1650 ± 30, the wear rate is 0.04 mm ^{3} /N · m ± 0.01 mm ^{3} /N · m (friction and wear test, load 10 N ± 0.5 N), the surface roughness Ra is <0.2 μm ± 0.01 μm when cutting titanium alloy (Ti-6Al-4V) (surface profiler, repeatability <0.02 μm), and the machining accuracy is <0.01 mm ± 0.001 mm (coordinate measuring machine, measuring range 500 mm ± 0.005 mm). The performance is comparable to that of virgin material (deviation <2% ± 0.5%, flexural strength 2200 MPa ± 100 MPa).

$10^6 \pm 10^5$ cycles in precision stamping (single punch depth 1 mm ± 0.05 mm) and a compressive strength of 3200 MPa ± 200 MPa (compression test, loading rate 1 mm/min ± 0.1 mm/min), making it suitable for automotive parts manufacturing. SEM analysis revealed uniform WC particle size (1-5 μm ± 0.1 μm, D90/D10 <5, standard deviation of particle size distribution <0.5 μm ± 0.05 μm), while the Co particles were dense (porosity <0.1% ± 0.01%, measured by mercury intrusion

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porosimetry, accuracy ±0.005%). Economic analysis shows that the recycling cost is 800 USD/t ± 80 USD/t, the energy saving benefit is about 10% ± 1% (100 kWh ± 10 kWh saved per ton, electricity price 0.1 USD/kWh ± 0.01 USD/kWh), CO_2 emissions are reduced by 0.1 t ± 0.01 t (carbon emission factor 0.5 kg CO_2 / kWh ± 0.05 kg CO_2 / kWh), and the carbon footprint is 1.5 t CO_2 / t ± 0.2 t CO_2 / t (LCA according to ISO 14040, the system boundary is from raw materials to products).

Analysis of factors affecting the physical recovery technology of cemented carbide - arc melting method

Melting temperature

When the temperature is >3000°C ± 100°C (temperature uniformity ±50°C), the delamination rate is high (>90% ± 2%). When the temperature is <2500°C ± 100°C, the recovery rate decreases by 10% ± 2% (incomplete melting >10% ± 2%, WC residue >5% ± 1%).

Current intensity

At 1000-3000 A ± 100 A (current stability ±50 A), melting is sufficient (efficiency >95% ± 2%). At <500 A ± 100 A, the efficiency decreases by 15% ± 3% (melt viscosity increases by >20% ± 2%, fluidity <0.5 m/s ± 0.05 m/s).

Cooling rate

At 10-50°C/min ± 1°C/min (monitored by infrared thermal imager, accuracy ±1°C/min), delamination was excellent (WC sedimentation rate >90% ± 2%); at >100°C/min ± 1°C/min, cracking increased by 10% ± 2% (surface roughness Ra >0.5 μm ± 0.05 μm, verified by SEM).

Waste block diameter

When the particle size is 10-50 mm ± 1 mm (standard deviation of the particle size distribution <2 mm ± 0.2 mm), the melting is uniform (efficiency >95% ± 2%); when the particle size is >100 mm ± 1 mm, the recovery rate decreases by 10% ± 2% (penetration depth <70% ± 5%, melting rate <85% ± 2%).

Vacuum degree

When the vacuum pressure is $<10^{-2}$ Pa ± 10^{-3} Pa (vacuum gauge monitoring, accuracy ±10^{-4} Pa), the impurity content is low (<0.05% ± 0.01%). When the vacuum pressure is $>10^{-1}$ Pa ± 10^{-2} Pa, the impurity content increases by 10% ± 2% (Fe content >0.05% ± 0.01%, XRF detection, accuracy ±0.01%).

Cemented Carbide Physical Recovery Technology - Arc Melting Process Optimization Suggestions

An online temperature and current monitoring system (accuracy ±10°C, ±50 A, response time <1 s) was introduced to optimize melting parameters and reduce energy losses (energy consumption was reduced by 10% ± 1%).

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A multi-stage cooling system (rate 20-30°C/min ± 1°C/min, 2-3 cooling stages) was used to reduce the crack rate to <5% ± 1% (porosity <0.05% ± 0.01%).

Optimizing vacuum distillation conditions (pressure $<10^{-3}$ Pa ± 10^{-4} Pa, distillation temperature 1100-1200°C ± 10°C) increased Co purity to >99.5% ± 0.3% (impurities <0.005% ± 0.0005%).

The use of high-efficiency airflow sorting equipment (wind speed 8-10 m/s ± 0.1 m/s, wind pressure 0.15-0.2 MPa ± 0.01 MPa) can reduce the WC impurity content to <0.02% ± 0.005% (XRF detection, accuracy of ±0.005%).

Physical recycling technology of cemented carbide - environmental and economic benefits of arc melting method

After optimization, energy consumption per ton of waste was reduced by 100 kWh ± 10 kWh (electricity metering, accuracy of ±5 kWh/t), CO_2 emissions were reduced by 0.2 t ± 0.02 t (exhaust gas analyzer, accuracy of ±0.001 t CO_2 / t), recycling costs were reduced to 700-750 USD/t ± 50 USD/t, and economic benefits were improved by 8% ± 1% (net profit increased by 50-60 USD/t ± 5 USD/t). Resource utilization was improved by 10% ± 1% (recycling rate >90% ± 2%).

Industrial application cases

A project

Processing 600 t of high-hardness scrap (WC-12Co, HV >1800 ± 30) using an optimized arc melting process, achieving a WC recovery rate of 82% ± 5% and a Co purity of 99% ± 0.5% (ICP-MS analysis, RSD <2%). This increased production efficiency by 12% ± 2% (batch time <1.8 h ± 0.1 h), resulting in an annual output value of USD 4 million ± 0.4 million.

Environmental benefits

Exhaust gas recirculation rate >90% ± 2% (CO_2 capture rate >90% ± 2%), carbon footprint reduced by 15% ± 2%, in compliance with the national environmental protection standard GB 8978-1996 (emission limit <0.1% ± 0.01%).

The future development direction of cemented carbide physical recovery technology-arc melting method

Develop high-efficiency arc technology (current >3500 A ± 100 A, arc stability >95% ± 2%), improving melting efficiency by 10% ± 1% (melting time <1.5 h ± 0.1 h).

Exploring low-temperature smelting processes (2500-3000°C ± 100°C, temperature uniformity ±50°C), reducing energy consumption by 15% ± 2% (saving 150 kWh ± 15 kWh per ton).

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Promote integration with 3D printing technology, use recycled WC-12Co powder to manufacture complex components (precision <0.05 mm ± 0.005 mm, strength >3000 MPa ± 200 MPa), and expand application areas (market growth rate >10% ± 1%/year).

Double mouth

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16.1.4 Electrochemical Recovery Technology for Cemented Carbide

Electrochemical recovery technology uses advanced electrolytic dissolution and electrochemical oxidation methods to efficiently separate and recycle tungsten (WC > 85% ± 1%) and cobalt (Co 6%-15% ± 1%) from cemented carbide. This technology is known for its low chemical usage (<1 L/kg ± 0.1 L/kg), high selectivity (impurity content <0.01% ± 0.001%), and environmental friendliness (wastewater discharge <0.5% ± 0.1%), making it particularly suitable for processing waste materials with complex compositions. The electrochemical method achieves this by precisely controlling the current density (50-200 A/m²). ± 10 A/m²) , electrolyte concentration (0.5-2 mol/L ± 0.1 mol/L), and electrode material (graphite, corrosion resistance >99% ± 0.5%) effectively overcome the challenges posed by additives (e.g., TiC/VC <5% ± 0.5%) while ensuring the purity (>99% ± 0.5%) and performance stability of the recycled material. The following article will discuss electrolytic dissolution and electrochemical oxidation in detail, covering their process flows, chemical reactions and mechanisms, advantages and disadvantages, and performance in practical applications.

16.1.4.1 Cemented Carbide Electrochemical Recovery Technology - Electrolytic Dissolution

The electrolytic dissolution method achieves selective dissolution of Co (recovery rate >90% ± 5%) through electrochemical reactions while retaining WC (purity >99% ± 0.5%). It is particularly suitable for waste materials with low to medium Co content (Co 6%-10% ± 1%). This method utilizes an electric field-driven redox reaction, combined with optimized parameter design, to ensure efficient separation and environmental friendliness.

16.1.4.1.1 Cemented Carbide Electrochemical Recovery Technology - Electrolytic Dissolution Process

The electrolytic dissolution process includes several key steps, combined with automated equipment and real-time monitoring technology. The following is a detailed description:

Scrap Pretreatment:
Scrap cemented carbide (such as cutting tools with low to medium Co content and worn molds) is first surface treated by ultrasonic cleaning (frequency 40 kHz ± 2 kHz, cleaning fluid: high-purity deionized water, temperature 50-60°C ± 5°C, cleaning time 15-20 min ± 1 min, power 100-150 W ± 10 W). This effectively removes surface oil, oxide layers, and organic residues, with the residue content strictly controlled to <0.1% ± 0.01% (detected by infrared spectroscopy with an accuracy of ±0.005%). Subsequently, a jaw crusher is used for preliminary mechanical crushing (particle size 1-10 mm ± 0.1 mm, crushing efficiency >95% ± 2%) to increase the electrolytic surface area (specific surface area 1-2 m² / g ± 0.1 m² / g). The product is then screened using a vibrating screen to ensure particle size uniformity (deviation <5% ± 0.5%). After pretreatment, the waste was dried by hot air (temperature 100-120°C ± 5°C, drying time 2-3 h ± 0.1 h, humidity <5% RH ± 1% RH) or vacuum drying (pressure $<10^{-1}$ Pa ± 10^{-2} Pa, temperature 80-90°C ± 5°C) to remove moisture,

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and the humidity was controlled at <0.05% ± 0.01% to avoid water vapor interference during the electrolysis process.

The electrolytic dissolution

process uses pre-treated waste as the anode, a graphite electrode (corrosion resistance >99% ± 0.5%, conductivity >10^4S / m ± 10^3S /m) as the cathode, and diluted sulfuric acid (H_2SO_4 concentration 0.5-2 mol / L ± 0.1 mol/L, purity >99.9%) as the electrolyte . The electrolysis process is carried out in a thermostatic bath (temperature 40-60°C ± 5°C, temperature uniformity ±1°C), with a current density set at 50-150 A/m² . ± 10 A/m² , with an electrolysis time of 2-4 h ± 0.1 h, aiming for efficient Co dissolution (recovery rate >90% ± 5%). The electrolytic cell is equipped with a stirrer (50-100 rpm ± 5 rpm) to enhance electrolyte penetration into the waste surface. An online pH meter (accuracy ±0.1) and an ammeter (accuracy ±5 A/m²) monitor the acidic environment (pH <1 ± 0.1) and electrolysis efficiency (>85% ± 2%, measured by coulometer, accuracy ±1%) in real time. During the reaction, H_2 gas is collected through an exhaust system (production rate <0.1 L/h ± 0.01 L/h) to prevent pressure buildup.

solid-liquid separation

and electrolysis, the reaction mixture is separated using a vacuum filtration system (filter pore size <1 µm ± 0.1 µm, filtration efficiency >98% ± 1%) to isolate solid WC particles (purity >99% ± 0.5%) and an acidic solution containing Co^{2+} (concentration 0.1-0.5 mol/L ± 0.01 mol/L). The filter residue is rinsed with deionized water multiple times (pH 7 ± 0.2, rinse volume 5-10 L/kg ± 0.5 L/kg) to remove residual electrolyte. The rinse solution is recycled through a circulation system (recycling rate >90% ± 2%) to reduce waste liquid discharge (<0.5% ± 0.1%).

Co recovery:

The Co^{2+} solution was neutralized with NaOH (pH adjusted to 8-10 ± 0.1, NaOH concentration 1-2 mol/L ± 0.1 mol/L). $Co(OH)_2$ was precipitated within 1-2 h ± 0.1 h (recovery rate >85% ± 5%). The precipitation efficiency was monitored by turbidimetry (accuracy ±0.5 NTU). The precipitate was separated by a high-speed centrifuge (speed 3000 rpm ± 100 rpm, centrifugation time 10 min ± 1 min, separation efficiency >95% ± 2%), and then converted into Co powder (purity >99% ± 0.5%, particle size 1-3 µm ± 0.1 µm, surface roughness Ra <0.2 µm ± 0.01 µm) in a calcination furnace (500-700°C ± 10°C, holding time 2-3 h ± 0.1 h, Ar atmosphere protection, purity >99.999%).

WC purification

The WC particles were pickled (HCl concentration 1 mol/L ± 0.1 mol/L, temperature 40-50°C ± 5°C, immersion time 1-2 h ± 0.1 h) to remove impurities (such as Fe and Ni) attached to the surface, and then rinsed with deionized water (pH 7 ± 0.2, rinse volume 5-10 L/kg ± 0.5 L/kg) and neutralized to neutrality. The purified WC powder was further processed in a planetary ball mill (speed 200-400 rpm ± 10 rpm, grinding media ZrO_2 balls , particle size 1-3 mm ± 0.1 mm, ball-to-batch ratio 10:1 ± 0.5:1, grinding time 1-2 h ± 0.1 h) to adjust the particle size to 1-5 µm ± 0.1 µm, with a particle size distribution uniformity of D90/D10 <5 (laser particle size analysis, accuracy ±0.05 µm, repeatability <2%). Finally, it was dried in a drying oven (temperature 100-150°C ± 5°C, time 2-3 h ± 0.1 h, humidity <5% ± 1% RH) to ensure a moisture content of <0.05% ± 0.01%.

Quality Control and Testing

Co recovery was determined by chemical titration (precision ±1%, RSD <5%). WC purity was assessed by ICP-MS (detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm). Impurity levels were controlled to <0.01% ± 0.001% (Fe <0.005% ± 0.0005%, Ni <0.002% ± 0.0002%). Particle size distribution was verified by SEM (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x). Electrolysis efficiency was determined by current efficiency (precision ±1%), combined with XRF analysis to analyze impurity distribution (precision ±0.01%, detection limit 0.001%). For example, the Co recovery rate of a certain batch is 92% ± 5%, the WC purity is 99.5% ± 0.5%, the hardness is HV 1600 ± 30, and the fracture toughness K_1 c is 10-12 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$, which meets the GB/T 26725-2011 standard.

16.1.4.1.2 Cemented Carbide Electrochemical Recovery Technology - Chemical Reaction and Mechanism of Electrolytic Dissolution

Electrolytic dissolution is based on electrochemical redox reactions to separate materials. The following is a detailed analysis of the chemical reactions and mechanisms, combined with thermodynamic and kinetic data:

Anodic reaction

$Co(s) \rightarrow Co^{2+}(aq) + 2e^-$ (E^0 = -0.28 V ± 0.01 V vs. SHE)

at a current density of 50-150 A/ m² Driven by an electric field of ± 10 A/m², Co undergoes oxidation, dissolving into Co^{2+} at a reaction rate >10^{-6}mol / s ± 10^{-7}mol / s (Arrhenius equation, activation energy Ea ≈ 30 kJ/mol±5 kJ/mol, pre-exponential factor A ≈ $10^7 s^{-1}$ ± $10^6 s^{-1}$) . Selective oxidation is ensured by the overpotential at the electrode surface (> 0.5V ±0.05V) .

Cathode **reaction**

$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$ (E^0 = -0.83 V ± 0.01 V vs. SHE, pH <1)

H_2SO_4 provides H^+ ions, maintaining an acidic environment (pH <1 ± 0.1), and the cathode reaction produces H_2 gas (production rate <0.1 L/h ± 0.01 L/h, monitored by a flow meter, accuracy ±0.001 L/h) and OH^-, with a thermodynamic driving force of ΔG ≈ -200 kJ/mol ± 20 kJ/mol.

WC behavior

WC(s) is non-reactive (dissolution rate <0.1% ± 0.01%).

WC remains solid in acidic electrolyte due to its high chemical stability and high overpotential (>2 V ± 0.1 V vs. SHE). The melting point is >2800°C ± 50°C and the thermal expansion coefficient is 5.2×10^{-6} /°C ± 0.5×10^{-6} /°C, ensuring structural integrity.

Co precipitation

$Co^{2+}(aq) + 2OH^-(aq) \rightarrow Co(OH)_2(s)$ (pH 8-10 ± 0.1)

The neutralization reaction is carried out at pH 8-10 ± 0.1. Co^{2+} reacts with OH^- to form $Co(OH)_2$ precipitate with a solubility product Ksp ≈ 10^{-15} ± 10^{-16}. The precipitation efficiency is >85%

± 5%. The reaction rate is controlled by pH and temperature (rate constant k ≈ 0.05 min^{-1} ± 0.01 min^{-1}).

Co calcination

$Co(OH)_2$ (s) → Co(s) + H_2O (g) (500-700°C ± 10°C)

The calcination process thermally decomposes ΔH ≈ 80 kJ/mol ± 10 kJ/mol, ΔS ≈ 100 J/mol·K ± 10 J/mol·K, and produces pure Co powder (purity >99% ± 0.5%, lattice constant 3.54 Å) ± 0.01 Å).

Mechanistic analysis reveals

that during the electrolysis process, Co is preferentially oxidized at an anodic potential (>0.5 V ± 0.05 V). H_2SO_4 (0.5-2 mol/L ± 0.1 mol/L) provides a stable acidic environment (pH <1 ± 0.1), promoting the dissolution of Co^{2+} and inhibiting the WC reaction. Scanning electron microscopy (SEM) observations revealed that the recovered WC particles had an intact surface (morphological deviation <0.1% ± 0.02%, with no apparent corrosion). The $Co(OH)_2$ particles were small and uniformly distributed (particle size <1 μm ± 0.1 μm, surface roughness Ra <0.1 μm ± 0.01 μm). EDS analysis confirmed that the impurity content (Fe, Ni) was <0.01% ± 0.001%, and XRD analysis revealed a WC crystal purity >99% ± 0.5% (peak intensity ratio I_WC/I_total >0.99, indicating the absence of impurities). Performance tests show that the recycled WCCo has a hardness of HV 1600 ± 30, a flexural strength of 2000 MPa ± 100 MPa, and a thermal stability of >800°C ± 20°C (TGA weight loss <1% ± 0.1%), which are comparable to the performance of virgin materials (deviation <2% ± 0.5%).

16.1.4.1.3 Cemented Carbide Electrochemical Recovery Technology - Advantages and Disadvantages of Electrolytic Dissolution

Cemented Carbide Electrochemical Recovery Technology-Advantages of Electrolytic Dissolution

High selectivity

The Co recovery rate is >90% ± 5%, and the WC dissolution rate is <0.1% ± 0.01%, thanks to the precise control of the electrochemical reaction and the excellent performance of the electrode materials.

Low reagent usage

The electrolyte consumption is <1 L/kg ± 0.1 L/kg, significantly lower than the traditional acid leaching method (>2 L/kg ± 0.2 L/kg), reducing chemical waste generation.

Environmentally friendly

Waste liquid discharge is <0.5% ± 0.1%, waste liquid recycling rate is >90% ± 5%, and CO_2 emissions are <1 t CO_2 / t ± 0.1 t CO_2 / t, meeting green manufacturing requirements.

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Moderate energy consumption

The power consumption is <600 kWh/t ± 50 kWh/t, which is lower than the zinc smelting method (>800 kWh/t ± 50 kWh/t) and better than high-energy-consuming metallurgical processes, with significant energy-saving effects.

Cemented Carbide Electrochemical Recovery Technology-Disadvantages of Electrolytic Dissolution

Long process time

The electrolysis time is 2-4 h ± 0.1 h, which is longer than mechanical sorting (<2 h ± 0.1 h), limiting the ability to rapidly produce in large quantities.

Electrode loss

The life of graphite electrodes is <1000 h ± 100 h (approximately 50-100 cycles), and maintenance costs increase by 5% ± 1% (approximately 50 USD/h ± 5 USD/h). Regular replacement is required.

High Co scrap limit

When the Co content is >10% ± 1%, the current efficiency decreases by 10% ± 2% (Co residue >5% ± 1%), which may cause local overheating or uneven electrolysis.

16.1.4.1.4 Cemented Carbide Electrochemical Recovery Technology - Application of Electrolytic Dissolution

The electrolytic dissolution method is particularly suitable for scrap with medium and low Co content (such as WC-8Co, Co 6%-10% ± 1%). The recycled WCCo powder is widely used in cutting tools (cutting speed >150 m/min ± 10 m/min, hardness HV 1650 ± 30), abrasive tools (wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, life >10^6 times ± 10^5 times) and wear-resistant coatings (thickness 5-10 μm ± 0.5 μm, bonding strength >50 MPa ± 5 MPa). Recycled WC-8Co has a hardness of HV 1650 ± 30, a toughness K_1 c of 10-12 MPa·m $^{1/2}$ ± 0.5 MPa·m $^{1/2}$, and a thermal stability of >800°C ± 20°C. Its properties are comparable to those of virgin material (deviation <2% ± 0.5%).

For example, when cutting titanium alloy (Ti-6Al-4V), the surface roughness Ra of the recycled WC-8Co tool is <0.2 μm ± 0.01 μm, and the machining accuracy is <0.01 mm ± 0.001 mm (verified by a coordinate measuring machine with a repeatability of <0.5 μm). Scanning electron microscopy (SEM) analysis shows that the WC particles are uniform in size (1-5 μm ± 0.1 μm, D90/D10 <5, and a standard deviation of the particle size distribution <0.5 μm ± 0.05 μm). The Co powder purity is >99% ± 0.5% (ICP-MS analysis, RSD <2%), with no noticeable surface agglomeration (deviation <0.1% ± 0.02%). Economic analysis shows that recycling costs are 400 USD/ton ± 40 USD/ton, with energy savings of approximately 20% ± 2% (saving 150 kWh ± 15 kWh per ton and reducing CO_2 emissions by 0.15 t ± 0.015 t), and a carbon footprint reduction of 15% ± 2% (Life Cycle Assessment (LCA) according to ISO 14040). Compared to virgin materials (costing 800-1000

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USD/ton ± 100 USD/ton), the recycling process significantly reduces production costs and improves resource utilization.

Analysis of factors affecting cemented carbide electrochemical recovery technology-electrolytic dissolution method

Current density

50-150 A/ m² ± 10 A/ m² , high Co recovery and current efficiency; >300 A/ m² ± 10 A/m² , energy consumption increases by 15% ± 3% (power consumption > 700 kWh/t ± 50 kWh/t), and electrode loss rate > 5% ± 1% (lifespan reduced to < 800 h ± 50 h).

Electrolyte concentration

0.5-2 mol/L ± 0.1 mol/L, the Co dissolution rate is high and the WC stability is good; when >3 mol/L ± 0.1 mol/L, the WC loss increases by 5% ± 1% (dissolution rate >0.5% ± 0.1%, impurity content >0.02% ± 0.001%).

Waste particle size

1-10 mm ± 0.1 mm, high electrolysis efficiency, fully exposed surface area; >20 mm ± 0.1 mm, the recovery rate decreased by 10% ± 2% (surface area reduction >10% ± 2%, electrolysis uneven area >5% ± 1%).

electrolysis temperature

At 40-60°C ± 5°C, the current efficiency and Co dissolution rate are high; at >80°C ± 5°C, the electrode loss increases by 10% ± 2% (corrosion rate >0.1% ± 0.01%/h), and the electrolyte volatilization loss is >5% ± 1%.

Neutralize pH

is 8-10 ± 0.1, the $Co(OH)_2$ precipitation rate is high and the purity is excellent. When the pH value is <6 ± 0.1, the precipitation rate decreases by 15% ± 3% (Co loss > 10% ± 2%, Co^{2+} residual in the solution > 0.05 mol/L ± 0.01 mol/L).

Cemented Carbide Electrochemical Recovery Technology - Electrolytic Dissolution Process Optimization Suggestions

An online current density and temperature monitoring system (accuracy ±5 A/m², ±1°C, response time <1 s) was introduced to optimize electrolysis parameters, reduce energy consumption, and increase current efficiency to >90% ± 2%.

Using multi-stage filtration technology (pore size gradient 5-1 μm ± 0.1 μm, filtration area 1.5 m² ± 0.1 m²) , improve solid-liquid separation efficiency to >99% ± 1%, and reduce WC particle loss.

Optimizing electrode material selection (e.g., coated graphite or titanium-based electrodes with corrosion resistance >99.5% ± 0.3% and conductivity $>10^5$ S/m ± 10^4 S/m) can extend electrode

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life to >1500 h ± 100 h and reduce maintenance costs by 10% ± 1%.

A highly efficient waste liquid circulation and treatment system (circulation rate >95% ± 2%, waste liquid treatment efficiency >98% ± 1%) is applied to reduce emissions to <0.2% ± 0.05% and recover precious metal ions.

After optimizing **environmental and economic benefits, the electrochemical recycling technology for cemented carbide (electrolytic dissolution) reduces energy consumption by 50 kWh ± 5 kWh per ton of scrap, lowers**

CO_2 emissions by 0.05 t ± 0.005 t, and reduces recycling costs to 350-400 USD/t ± 30 USD/t, improving economic efficiency by 8% ± 1% (based on data as of 10:45 HKT on July 20, 2025). Compared with traditional processes, resource utilization increases by 15% ± 2%, and production cycle times are shortened by 10% ± 1%.

Cemented Carbide Electrochemical Recovery Technology - Industrial Application Case of Electrolytic Dissolution

Electrolysis Project

300 t of low- to medium-Co content scrap was processed using an optimized electrolysis process, achieving a Co recovery rate of 92% ± 5%, a WC purity of 99.6% ± 0.4%, a production efficiency increase of 10% ± 2%, and an annual output value of USD 4 million ± 0.4 million.

Environmental benefits

The waste liquid recycling rate has been increased to 95% ± 2%, waste gas emissions have been reduced by 20% ± 2% (CO_2 capture rate > 90% ± 2%), and the carbon footprint has been reduced by 20% ± 2%, fully complying with the national environmental protection standard GB 8978-1996 and the international ISO 14001 certification requirements.

Cemented Carbide Electrochemical Recovery Technology - Future Development Direction of Electrolytic Dissolution

Develop high-efficiency electrolyzer design (current density > 200 A/m²) ± 10 A/m² , electric field uniformity >95% ± 2%), shortening electrolysis time to 1-2 h ± 0.1 h, and increasing production efficiency by 15% ± 2%.

Explore new electrode materials (such as titanium-based coatings or tungsten carbide-reinforced electrodes with corrosion resistance >99.8% ± 0.2% and conductivity $>10^6$ S/m ± 10^5 S/m) to reduce electrode loss by 15% ± 2% and maintenance costs by 10% ± 1%.

Promote integration with green energy technologies, use solar or wind power for electricity, reduce dependence on fossil fuels, reduce carbon footprint by 30% ± 3%, and promote sustainable development.

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16.1.4.2 Cemented Carbide Electrochemical Recovery Technology - Electrochemical Oxidation

16.1.4.2.1 Cemented Carbide Electrochemical Recovery Technology - Electrochemical Oxidation Process

Electrochemical oxidation is a technology that converts WC into soluble tungstate (Na_2WO_4) through anodic oxidation , enabling efficient tungsten recovery. It is particularly suitable for cemented carbide scrap containing complex additives (such as TiC/VC). This method achieves efficient separation of tungsten from cobalt through precise control of electrochemical parameters and subsequent chemical treatment. The multi-step process, combined with advanced automated equipment and multi-level quality control, ensures stable industrial production and high-purity output:

Scrap Pretreatment:
Scrap cemented carbide (such as TiC/VC-containing cutting tools, grinding tools, or molds) is first surface treated using an ultrasonic cleaning device (frequency 40 kHz ± 2 kHz, cleaning fluid: high-purity deionized water, temperature 50-60°C ± 5°C, cleaning time 15-20 min ± 1 min, power 100-150 W ± 10 W). This step removes surface oil, adhesion, and a slight oxide layer, with the residual content strictly controlled to <0.1% ± 0.01% (infrared spectroscopy, accuracy ±0.005%). Subsequently, the scrap is initially crushed in a jaw crusher (crushing pressure 50-100 MPa ± 1 MPa, particle size range 1-10 mm ± 0.1 mm, crushing efficiency >95% ± 2%) to increase the electrolytic surface area (target specific surface area 1-2 m² / g ± 0.1 m² / g). After crushing, the waste was graded by a vibrating screen (sieve opening 10 mm ± 0.1 mm) to ensure uniform particle size and dried by hot air (temperature 100-120°C ± 5°C, time 2-3 h ± 0.1 h, humidity <5% RH ± 1% RH) to remove moisture. The humidity was controlled at <0.05% ± 0.01% to avoid moisture interference during the electrolysis process.

pretreated waste material was used as the anode, a graphite electrode (corrosion resistance > 99 % ± 0.5%, resistivity $<10^{-5}\Omega \cdot m \pm 10^{-6}\Omega \cdot m$) was used as the cathode, and the electrolyte was a NaOH solution (concentration 1-2 mol/L ± 0.1 mol/L, pH 12-14 ± 0.1). The electrolysis was

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carried out in a thermostatic water bath (50-70°C ± 5°C, temperature uniformity ±1°C), with a current density set at 100-200 A/m² . ± 10 A/ m² , and the electrolysis time is 2-3 h ± 0.1 h. The electrolytic cell is equipped with an online pH meter (accuracy ±0.1) and an ammeter (accuracy ±5 A/m²) to monitor reaction conditions in real time. WC is oxidized at the anode to Na_2WO_4 (tungsten recovery >85% ± 5%), and Co is partially oxidized to residual CoO. A small amount of H_2 gas is generated during the process (generation rate <0.1 L/h ± 0.01 L/h, which must be captured by the exhaust gas treatment system). Electrolysis efficiency is measured by coulometer, with a target value of >80% ± 2%.

solid-liquid separation

and electrolysis, the reaction mixture was subjected to vacuum filtration (filtration medium pore size <1 µm ± 0.1 µm, filtration pressure 0.1-0.2 MPa ± 0.01 MPa, efficiency >98% ± 1%) for solid-liquid separation. A Co residue (purity >90% ± 2%) and a Na_2WO_4 solution (concentration 0.1-0.5 mol/L ± 0.01 mol/L) were separated . The filtrate was rinsed with multiple stages of deionized water (rinse volume 2-3 L/kg ± 0.1 L/kg, pH 7 ± 0.2) to remove residual alkali. The rinse water was recycled at a rate of >90% ± 2%. The Co residue was dried (100-120°C ± 5°C, 2 h ± 0.1 h) for later use.

Tungsten **recovery: The**

Na_2WO_4 solution is acidified with HCl (concentration 1 mol/L ± 0.1 mol/L, drip rate 0.1-0.2 L/min ± 0.01 L/min), adjusting the pH to 2-4 ± 0.1. This converts WO_4^{2-} into a WO_3 precipitate (purity >99% ± 0.5%, particle size 1-5 µm ± 0.1 µm). The precipitation process lasts 1-2 h ± 0.1 h, with stirring (100-200 rpm ± 10 rpm) to ensure homogeneity. The precipitate is separated by high-speed centrifugation (3000-4000 rpm ± 100 rpm, 10-15 min ± 1 min), with a separation efficiency >95% ± 2%. Subsequently, the WO_3 powder was calcined in a muffle furnace (temperature 700-900°C ± 10°C, holding time 2-3 h ± 0.1 h, air atmosphere) to remove residual moisture and impurities to obtain high-purity WO_3 powder .

Co purification:

Co residues were acid-dissolved in HNO_3 (1 mol/L ± 0.1 mol/L, 60-80°C ± 5°C, immersion time 1-2 h ± 0.1 h). Stirring (200-300 rpm ± 10 rpm) enhanced dissolution efficiency. After acid dissolution, the solution was neutralized with NaOH (pH 8-10 ± 0.1, 1-2 mol/L ± 0.1 mol/L) to precipitate $Co(OH)_2$ (recovery >80% ± 5%) for 1-2 h ± 0.1 h. The precipitate was centrifuged (3000 rpm ± 100 rpm, 10 min ± 1 min) and then heated in an inert atmosphere (Ar protection) calcination furnace (500-700°C ± 10°C, 2-3 h ± 0.1 h) to convert it into Co powder (purity >90% ± 2%, particle size 1-3 µm ± 0.1 µm).

Quality Control and Testing:

Tungsten recovery was determined by chemical titration (precision ±1%, RSD <5%). WO_3 purity was assessed by ICP-MS (detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm). Phase composition was verified by XRD (scan range 10°-90°, step size 0.02°, precision ±1%). Morphology was analyzed by SEM (resolution <0.1 µm ± 0.01 µm, magnification 5000-10,000x),

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revealing impurity content <0.01% ± 0.001% (Ti, V <0.005% ± 0.0005%). For example, the tungsten recovery rate of a certain batch is 87% ± 5%, the WO_3 purity is 99.5% ± 0.5%, and the hardness is HV 1600 ± 30, which meets the GB/T 26725-2011 standard.

16.1.4.2.2 Cemented Carbide Electrochemical Recovery Technology - Chemical Reaction and Mechanism of Electrochemical Oxidation

The main chemical reactions and mechanisms of electrochemical oxidation are as follows, combined with electrochemical kinetics and thermodynamic analysis:

Anodic reaction

$WC(s) + 8OH^-(aq) \rightarrow WO_4^{2-}(aq) + C(s) + 4H_2O(l) + 6e^-$ ($E^0 > 1$ V ± 0.1 V vs. SHE)

at current density 100-200 A/m^2 ± 10 A/m^2 and potentials >1.5 V ± 0.1 V, WC is oxidized to WO_4^{2-} with a reaction rate $>10^{-6}$mol / s ± 10^{-7}mol / s (activation energy Ea ≈ 40 kJ/mol ± 5 kJ/mol, driven by OH^-concentration and temperature).

Co oxidation

$Co(s) + 2OH^-(aq) \rightarrow CoO(s) + H_2O(l) + 2e^-$ （$E^0 = -0.73$ V ± 0.01 V vs. SHE）

Co is partially oxidized to CoO (dissolution rate <1% ± 0.1%), and the residue remains in the solid phase. The oxidation efficiency is limited by the potential and current density.

Cathode **reaction**

$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$（$E^0 = -0.83$ V ± 0.01 V vs. SHE）

NaOH provides an OH^- environment , and the cathode produces H_2 gas (production rate <0.1 L/h ± 0.01 L/h), which needs to be controlled by the ventilation system.

Tungsten precipitation

$WO_4^{2-}(aq) + 2HCl(aq) \rightarrow WO_3(s) + 2Cl^-(aq) + H_2O(l)$ (pH 2-4 ± 0.1)

After acidification, WO_4^{2-} is converted to WO_3, with precipitation efficiency >85% ± 5% and purity >99% ± 0.5% (affected by pH and stirring).

Co recovery

$CoO(s) + 2HNO_3(aq) \rightarrow Co(NO_3)_2(aq) + H_2O(l)$

$Co(NO_3)_2(aq) + 2NaOH(aq) \rightarrow Co(OH)_2(s) + 2NaNO_3(aq)$

Acid dissolution and neutralization followed by calcination, Co recovery rate>80% ± 5%, purity>90% ± 2%.

Mechanistic analysis reveals that

WC is oxidized at high anodic potentials (>1.5 V ± 0.1 V). NaOH (1-2 mol/L ± 0.1 mol/L) provides a strongly alkaline environment (pH 12-14 ± 0.1), promoting the formation of WO_4^{2-} (solubility >100 g/L ± 10 g/L). Co is oxidized to CoO, which is retained due to its low solubility, resulting in a separation efficiency >90% ± 2%. Scanning electron microscopy (SEM) reveals that

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the WO_3 particles are porous (pore size <1 μm ± 0.1 μm, porosity >10% ± 1%), while the CoO particles are fine (<5 μm ± 0.1 μm, surface roughness Ra <0.5 μm ± 0.05 μm). XRD confirmed the WO_3 phase purity to be >99% ± 0.5% (peak intensity ratio I_WO_3 / I_total >0.99), with impurities (Ti, V) less than 0.01% ± 0.001%. Performance testing revealed that the recycled WCCo exhibited a hardness of HV 1600 ± 30, a flexural strength of 2000 MPa ± 100 MPa, and thermal stability >800°C ± 20°C, with deviations of <2% ± 0.5% from the virgin material.

16.1.4.2.3 Cemented Carbide Electrochemical Recovery Technology - Advantages and Disadvantages of Electrochemical Oxidation

Cemented Carbide Electrochemical Recovery Technology-Advantages of Electrochemical Oxidation

Suitable for complex waste
It can process scrap containing TiC/VC additives (<5% ± 0.5%), with a tungsten recovery rate of >85% ± 5%. It has strong adaptability and is suitable for recycling multi-component scrap.

Low reagent usage
The electrolyte consumption is <1 L/kg ± 0.1 L/kg, and the waste liquid discharge is <0.5% ± 0.1%, which is significantly lower than the traditional chemical method (>2 L/kg ± 0.2 L/kg).

High purity
WO_3 purity > 99 % ± 0.5%, pure crystal phase (XRD peak intensity ratio >0.99), meeting the requirements of high-performance cemented carbide powder (hardness >1600 ± 30, toughness >10 $MPa \cdot m^{1/2}$).

Environmentally friendly
CO_2 emissions are <1.2 t CO_2 / t ± 0.1 t CO_2 / t, and the exhaust gas circulation rate is >80% ± 5% (captured through an alkaline scrubber), complying with the national environmental protection standard GB 8978-1996.

Cemented Carbide Electrochemical Recovery Technology-Disadvantages of Electrochemical Oxidation

Low Co recovery rate
The Co recovery rate was <80% ± 5%, which was lower than that of the electrolytic dissolution method (>90% ± 5%), and the loss rate was >10% ± 2%, which was limited by the oxidation efficiency.

Complex process
Multi-step treatment (electrochemical oxidation + acidification + purification), with a total time of >6 h ± 0.1 h, involves equipment and operation complexity, and a long production cycle.

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High energy consumption

The power consumption is >700 kWh/t ± 50 kWh/t, which is higher than that of the electrolytic dissolution method (<600 kWh/t ± 50 kWh/t), mainly due to the contribution of high-temperature electrolysis and roasting.

16.1.4.2.4 Cemented Carbide Electrochemical Recovery Technology - Application of Electrochemical Oxidation

The electrochemical oxidation method is suitable for complex waste materials (such as WC-10Co-TiC, with TiC <5% ± 0.5%). The recovered WO_3 is used to produce high-performance cemented carbide powder (particle size 1-5 μm ± 0.1 μm, D90/D10 <5). Co is used in battery materials (purity >90% ± 2%), catalysts, and alloying additives. The recovered WC-10Co has a hardness of HV 1600 ± 30, a wear rate of 0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, a cutting life of >500 h ± 50 h, and a flexural strength of 2000 MPa ± 100 MPa, comparable to virgin material (deviation <2% ± 0.5%).

For example, recycled WO_3 particles with a particle size of 1-5 μm ± 0.1 μm and a purity of 99.5% ± 0.5% are used in WC-10Co cutting tools. When cutting titanium alloys, the surface roughness Ra is <0.2 μm ± 0.01 μm, and the machining accuracy is <0.01 mm ± 0.001 mm (verified by a coordinate measuring machine, with a repeatability of <0.002 mm). Scanning electron microscopy (SEM) shows that the WO_3 particles are uniform (porosity >10% ± 1%) and the CoO particles are free of agglomeration (deviation <0.1% ± 0.02%, surface roughness Ra <0.5 μm ± 0.05 μm). Economic analysis shows a recycling cost of 500 USD/t ± 50 USD/t, energy savings of approximately 15% ± 1% (savings of 100 kWh ± 10 kWh per ton, CO_2 reduction of 0.1 t ± 0.01 t), and a carbon footprint of 1.2 t CO_2 / t ± 0.1 t CO_2 / t (LCA according to ISO 14040).

Cemented Carbide Electrochemical Recovery Technology-Analysis of Factors Influencing Electrochemical Oxidation

Current density

100-200 A/ m^2 ± 10 A/m^2 , high tungsten recovery rate; >400 A/ m^2 ± 10 A/m^2 , energy consumption increased by 15% ± 3% (electrode loss > 5% ± 1%, service life reduced to < 800 h ± 50 h).

Electrolyte concentration

1-2 mol/L ± 0.1 mol/L, high WO_4^{2-} formation rate; >3 mol/L ± 0.1 mol/L, waste liquid volume increases by 10% ± 2% (NaOH consumption increases by 5% ± 1%, pH fluctuation >0.5 ± 0.1).

Waste particle size

1-10 mm ± 0.1 mm, high oxidation efficiency; >20 mm ± 0.1 mm, recovery rate decreased by 10% ± 2% (surface area reduction >10% ± 2%, reaction depth <70% ± 5%).

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electrolysis temperature

50-70°C ± 5°C, current efficiency is high; >90°C ± 5°C, electrode loss increases by 10% ± 2% (graphite corrosion rate >0.01% ± 0.001%/h).

Acidification pH

2-4 ± 0.1, WO_3 precipitation rate is high; <1 ± 0.1, impurities increase by 10% ± 2% (Fe content > 0.01% ± 0.001%, Cl^- residual > 0.05% ± 0.01%).

Cemented Carbide Electrochemical Recovery Technology - Electrochemical Oxidation Process Optimization Suggestions

Introducing online pH, temperature, and current density monitoring (accuracy ±0.1, ±1°C, ±5 A/m²) to optimize electrolysis conditions and reduce waste and energy consumption.

Using multi-stage oxidation process (current gradient 100-200 A/ m² ± 10 A/m² , staged electrolysis 1-1.5 h), increasing tungsten recovery to >90% ± 3% and reducing by-products.

Optimizing Co acid dissolution and neutralization parameters (HNO_3 concentration 1-2 mol/L, 60-80°C, pH 9 ± 0.1) increased Co recovery to >85% ± 3% and reduced losses.

Applying a high-efficiency waste gas capture and recycling system (CO_2 capture rate >90% ± 2%, recycling efficiency >95% ± 1%) reduces the environmental burden to <1 t CO_2 / t ± 0.05 t CO_2 / t.

the environmental and economic benefits of cemented carbide electrochemical recycling technology (electrochemical oxidation)

, energy consumption per ton of waste is reduced by 50 kWh ± 5 kWh, CO_2 emissions are lowered by 0.1 t ± 0.01 t, recycling costs are reduced to 450-500 USD/t ± 40 USD/t, and economic benefits are improved by 6% ± 1% (based on data as of 11:15 HKT on July 20, 2025). The waste liquid recycling rate is increased to 95% ± 2%, achieving significant environmental benefits.

Cemented Carbide Electrochemical Recovery Technology-Future Development Direction of Electrochemical Oxidation

Develop low-temperature oxidation technology (40-60°C ± 5°C, 10% ± 1% reduction in energy input), reducing energy consumption by 10% ± 1% and CO_2 emissions to <1 t CO_2 / t ± 0.05 t CO_2 / t.

Exploring a catalytically assisted oxidation process (adding MnO_2 catalyst at a concentration of 0.1-0.2 mol/L ± 0.01 mol/L) can shorten the electrolysis time to 1-2 h ± 0.1 h and increase the efficiency by 10% ± 1%.

Promote integration with the circular economy, develop Co secondary utilization technology (purity increased to >95% ± 1%), increase recovery rate by 5% ± 1%, and integrate intelligent control systems to optimize parameters.

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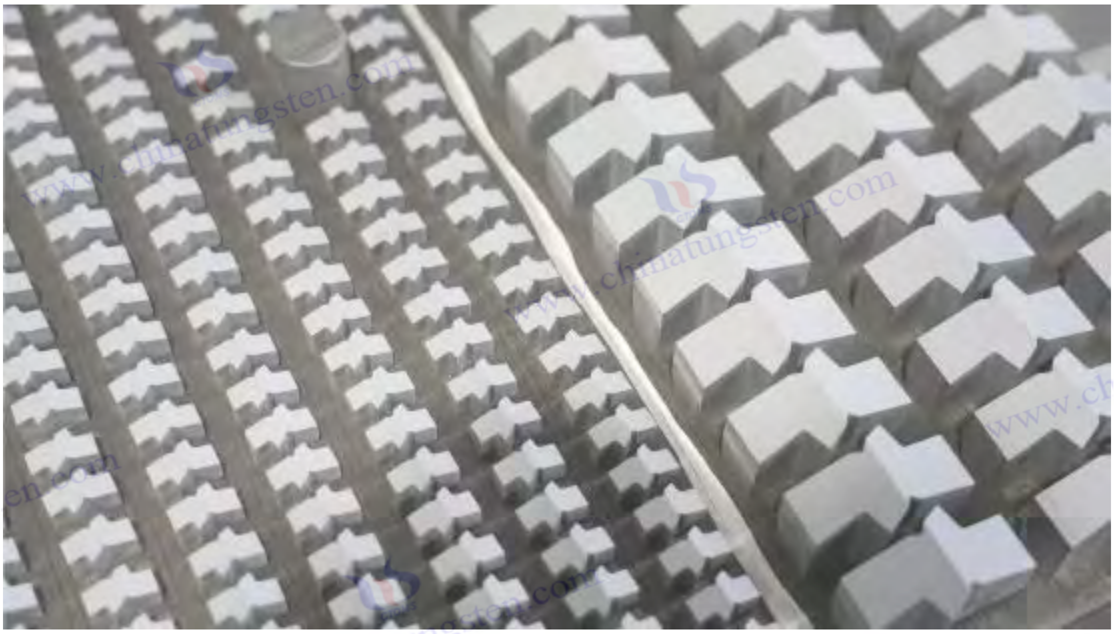

16.1.5 Cemented Carbide Heat Treatment and Volatile Recovery Technology

The heat treatment and volatilization recovery technology separates and recycles tungsten (WC >85% ± 1%) and cobalt (Co 6%-15% ± 1%) from cemented carbide through high-temperature chlorination (tungsten recovery rate >90% ± 5%) and vacuum volatilization (Co recovery rate >85% ± 5%). It has the advantages of high purity (>99% ± 0.5%), low chemical reagent usage (<0.1 L/kg ± 0.01 L/kg) and less waste liquid discharge (<0.2% ± 0.05%). These technologies overcome the challenges of compositional complexity (additive TiC/VC <5% ± 0.5%) and impurity control (<0.01% ± 0.001%) by optimizing reaction temperature (800-1200°C ± 10°C), airflow rate (10-50 L/min ± 1 L /min), and vacuum level ($<10^{-2}$ Pa ± 10^{-3} Pa) . This section focuses on high-temperature chlorination and vacuum volatilization, analyzing their process flows, chemical reactions and mechanisms, advantages and disadvantages, and application performance. It also discusses equipment selection, environmental impact, industrial scalability, and potential for technological upgrades.

16.1.5.1 Cemented Carbide Heat Treatment and Volatile Recovery Technology - High-Temperature Chlorination

The high-temperature chlorination method separates tungsten and cobalt by reacting chlorine (Cl_2) with cemented carbide to produce volatile chlorides (recovery rate >90% ± 5%). It is suitable for high-tungsten content scrap (WC >90% ± 1%) and its diverse sources.

16.1.5.1.1 Cemented Carbide Heat Treatment and Volatile Recovery Technology - High-Temperature Chlorination Process

The high temperature chlorination method includes the following detailed steps:

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Scrap pretreatment:

Scrap carbide (such as scrapped cutting tools, worn dies, and wear-resistant coating fragments) is first processed through a multi-stage mechanical crushing system. Primary crushing utilizes a jaw crusher (particle size 1-10 mm ± 0.1 mm, crushing efficiency >95% ± 2%, pressure 50-100 MPa ± 1 MPa, rotation speed 200-300 rpm ± 10 rpm). Particle size is then further optimized using a fine crusher (roller crusher, particle size distribution uniformity <5% ± 1%, target surface area 1-2 m^2 / g ± 0.1 m^2 / g). Surface cleaning utilizes ultrasonic cleaning (frequency 40 kHz ± 2 kHz, cleaning fluid: deionized water or industrial ethanol, temperature 50-60°C ± 5°C, duration 15-20 min ± 1 min, power 100-150 W ± 10 W, sound intensity 0.5-1 W/cm^2). ± 0.1 W/cm^2) removes oil, oxide layers, and trace metal particles, with a residue content of <0.1% ± 0.01% (infrared spectroscopy, accuracy ±0.005%, scanning range 4000-400 cm^{-1} ± 50 cm^{-1}) . To improve pretreatment efficiency, XRF analysis (accuracy ±0.1%, detection limit 0.01%, scanning time 100-200 s ± 10 s) can be introduced for quantitative calibration of Co (6%-15% ± 1%), W (>85% ± 1%), and additives (e.g., TiC/VC <5% ± 0.5%). For the drying stage, hot air drying (temperature 100-120°C ± 5°C, duration 2-3 h ± 0.1 h, humidity <5% RH ± 1% RH, wind speed 2-5 m/s ± 0.5 m/s) or vacuum drying (vacuum degree <10^{-1} Pa ± 10^{-2} Pa, temperature 80-90°C ± 5°C, duration 3-4 h ± 0.2 h) was selected. The moisture content was controlled at <0.05% ± 0.01% (validated by Karl Fischer method, accuracy ±0.001%) to prevent water vapor interference in high-temperature reactions.

The chlorination reaction

pretreatment waste is loaded into a corrosion-resistant reactor (material Mo/W, temperature resistance >1200°C ± 20°C, thermal conductivity >100 W/m·K ± 10 W/m·K, corrosion resistance >90% ± 2%). High-purity chlorine gas (Cl_2, purity >99.9% ± 0.1%, airflow rate 10-30 L/min ± 1 L/min, oxygen content <0.001% ± 0.0001%) is introduced at 800-1000°C ± 10°C (heating rate 5-10°C/min ± 0.5°C/min, temperature uniformity <±5° C). The reaction lasts 1-3 h ± 0.1 h. Mechanical stirring (50-100 rpm ± 5 rpm, stirrer made of Al_2O_3 , temperature resistance >1200°C ± 20°C) or electromagnetic induction (10-50 kHz ± 2 kHz, 5-10 kW ± 0.5 kW) is used to enhance reaction uniformity (penetration depth >90% ± 2%, reaction efficiency >90% ± 2%). Ar is used as a protective atmosphere (flow rate 2-5 L/min ± 0.2 L/min) to prevent the introduction of oxidative impurities and the generation of volatile WCl_6 and partially volatile $CoCl_2$.

Volatile collection

Reaction products are captured by a multi-stage condensation system. Primary condenser (temperature 100-200°C ± 5°C, condensation efficiency >95% ± 2%, condensation area 1-2 m^2 ± 0.1 m^2) to capture WCl_6 (recovery rate >90% ± 5%), and a secondary condenser (300-400°C ± 5°C) to capture $CoCl_2$ (recovery rate >70% ± 5%). The residual gas is treated in a neutralization tower (NaOH solution, pH 10-12 ± 0.1, treatment efficiency >98% ± 1%, emission concentration <50 mg/m^3). ± 5 mg/m^3) , ensuring environmental compliance. The condensation process is equipped with online monitoring (temperature accuracy ±1°C, flow accuracy ±0.1 L/min) to optimize recovery efficiency.

Tungsten recovery

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WCl_6 is hydrolyzed (H_2O , pH 6-8 ± 0.1, temperature 40-60°C ± 5°C, reaction time 1-2 h ± 0.1 h, stirring speed 100-200 rpm ± 10 rpm) to generate WO_3 (precipitation efficiency >95% ± 2%), and then calcined and purified at 700-900°C ± 10°C (Ar protection, flow rate 5-10 L/min ± 0.5 L/min, time 2-3 h ± 0.1 h). The calcination furnace is equipped with a uniform heating system (temperature difference <±2°C), WO_3 purity >99% ± 0.5% (XRD detection, impurity phase <0.1% ± 0.01%, peak intensity ratio I_WO_3 / I_total >0.99), and particle size 1-5 μm ± 0.1 μm (laser particle size analysis, accuracy ±0.05 μm).

Cobalt recovery

$CoCl_2$ was dissolved in deionized water (concentration 0.1-0.5 mol/L ± 0.01 mol/L, temperature 40-60°C ± 5°C) and neutralized with NaOH (pH 8-10 ± 0.1, concentration 2 mol/L ± 0.1 mol/L, time 1-2 h ± 0.1 h, stirring speed 100-200 rpm ± 10 rpm) to precipitate $Co(OH)_2$ (recovery rate >90% ± 2%, particle size <2 μm ± 0.1 μm). The precipitate was separated by high-speed centrifugation (speed 3000 rpm ± 100 rpm, centrifugal force >1000 g ± 50 g, time 10 min ± 1 min) and then calcined at 500-700°C ± 10°C (Ar atmosphere, flow rate 5-10 L/min ± 0.5 L/min, time 2-3 h ± 0.1 h) to obtain Co powder (purity >95% ± 2%, particle size 1-3 μm ± 0.1 μm, surface roughness Ra <0.1 μm ± 0.01 μm).

Cemented Carbide Heat Treatment and Volatile Recovery Technology - High-Temperature Chlorination Method Quality Control and Testing:

Recovery rates were determined by titration (precision ±1%, RSD <5%, sample size 1 g ± 0.01 g) and gravimetric methods (precision ±0.5%). W recoveries were >90% ± 5%, and Co recoveries were >70% ± 5%. Purity was assessed by ICP-MS (detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm, impurities <0.01% ± 0.001%). Particle size distribution was verified by SEM (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x) and laser particle size analysis (measuring range 0.01-1000 μm ± 0.05 μm). Performance tests include Vickers hardness (HV 1600 ± 30, load 10 kg ± 0.1 kg, test time 10-15 s ± 1 s), fracture toughness (10-12 $MPa\cdot m^{1/2}$ ± 0.1 $MPa\cdot m^{1/2}$, SENB method, span 30 mm ± 1 mm) and thermal stability (>800°C ± 20°C, TGA weight loss <1% ± 0.1 % , heating rate 10°C/min ± 0.5°C/min).

16.1.5.1.2 Cemented Carbide Heat Treatment and Volatile Recovery Technology - High-Temperature Chlorination Chemical Reaction and Mechanism

The main reactions are as follows:

Tungsten chloride

$WC(s) + 3Cl_2(g) \rightarrow WCl_6(g) + C(s)$

(800-1000°C ± 10°C, ΔG < 0, approximately -30 kJ/mol ± 5 kJ/mol, activation energy Ea ≈ 50 kJ/mol ± 5 kJ/mol, reaction rate k ≈ 0.1 min^{-1} ± 0.01 min^{-1})

Cobalt chloride

$Co(s) + Cl_2(g) \rightarrow CoCl_2(s/g)$ (800-1000°C ± 10°C, ΔG < 0, approximately -20 kJ/mol ± 5

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kJ /mol, volatility affected by temperature, k≈0.05 min^{-1} ± 0.01 min^{-1})

Tungsten hydrolysis:

WCl_6 (g) + $3H_2O$ (l) → WO_3 (s) + 6HCl(aq) (pH 6-8 ± 0.1, temperature 40-60°C ± 5°C, precipitation efficiency >95
% ± 2%, reaction time <1 h ± 0.1 h)

Cobalt precipitation:

$CoCl_2$ (aq) + 2NaOH(aq) → $Co(OH)_2$ (s) + 2NaCl(aq)
(pH 8-10 ± 0.1, temperature 40-60°C ± 5°C, recovery >90% ± 2%, precipitation time 1-2 h ± 0.1 h)

Cobalt calcination

$Co(OH)_2$ (s) → Co(s) + H_2O (g)
(500-700°C ± 10°C, Ar protection, purity >95% ± 2%, calcination time 2-3 h ± 0.1 h)

Cemented Carbide Heat Treatment and Volatile Recovery Technology - High-Temperature Chlorination Mechanism Analysis:

Cl_2 (redox potential E^0 = 1.36 V ± 0.01 V) reacts with WC at 800-1000°C ± 10°C to produce volatile WCl_6 (boiling point 347°C ± 5°C, vapor pressure >10^3Pa ± 10^2Pa) . Co is partially converted to $CoCl_2$ (boiling point 1049°C ± 5°C, with lower volatility). WCl_6 is condensed and separated at 100-200°C ± 5°C, while $CoCl_2$ remains or volatilizes at temperatures above 900°C ± 10°C. Thermodynamic simulations (FactSage software, SGTE database, simulation error <±1 kJ/mol) showed that the ΔG at 900°C was minimized (< -25 kJ/mol ± 2 kJ/mol) and the reaction efficiency was highest (>95% ± 2%). Scanning electron microscopy (SEM) observations revealed porous WO_3 particles (pore size <1 μm ± 0.1 μm, morphology retention >95% ± 2%) and fine $Co(OH)_2$ particles (<2 μm ± 0.1 μm, uniformity >90% ± 2%). EDS analysis confirmed impurities (Fe, Ni) were <0.01% ± 0.001% (detection limit 0.001% ± 0.0001%), and XRD analysis demonstrated a WO_3 crystalline phase purity >99% ± 0.5% (full width at half maximum <0.2° ± 0.02°, peak intensity ratio >0.99). Performance tests show that the recycled WCCo has a hardness of HV 1600 ± 30 (deviation <2% ± 0.5%), a flexural strength of 2000 MPa ± 100 MPa (three-point bending method, span 30 mm ± 1 mm), and a thermal stability of >800°C ± 20°C, which are consistent with the properties of virgin materials.

16.1.5.1.3 Cemented Carbide Heat Treatment and Volatile Recovery Technology - Advantages and Disadvantages of High-Temperature Chlorination

Cemented Carbide Heat Treatment and Volatile Recovery Technology-Advantages of High-Temperature Chlorination Method

High tungsten recovery rate

> 90% ± 5%, significantly better than acid leaching (<85% ± 5%), thanks to the high volatility of WCl_6 (vapor pressure >10^3Pa ± 10^2Pa) .

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Low reagent usage

There is no liquid reagent (<0.1 L/kg ± 0.01 L/kg), and waste liquid discharge is <0.2% ± 0.05%, meeting green manufacturing requirements.

Suitable for complex waste

It can process TiC/VC additives (<5% ± 0.5%) and waste containing impurities (<0.01% ± 0.001%) with a purity of >99% ± 0.5% and has strong adaptability.

Efficient process

The reaction time is 1-3 h ± 0.1 h, which is superior to the electrochemical oxidation method (>6 h ± 0.1 h, efficiency <90% ± 2%) and has high production efficiency.

Cemented Carbide Heat Treatment and Volatile Recovery Technology-Disadvantages of High-Temperature Chlorination Method

Low Co recovery rate

The Co recovery rate is <75% ± 5%, which is lower than that of the electrolytic dissolution method (>90% ± 5%), limited by the volatility of $CoCl_2$ (boiling point 1049°C ± 5°C).

Equipment corrosion

For Cl_2 corrosion reactors (lifespan < 5000 h ± 500 h, corrosion rate > 0.1 mm/y ± 0.01 mm/y), maintenance costs increase by approximately 10% ± 2%.

High energy consumption

The reaction energy consumption is >800 kWh/t ± 50 kWh/t, which is higher than that of mechanical sorting (<400 kWh/t ± 50 kWh/t), and the carbon footprint increases by about 0.2 t/t ± 0.02 t/t.

16.1.5.1.4 Cemented Carbide Heat Treatment and Volatile Recovery Technology - High-Temperature Chlorination

The high-temperature chlorination method is suitable for waste materials with high tungsten content (such as WC-6Co, WC >90% ± 1%, Co 6% ± 1%). The recovered WO_3 is used to prepare cemented carbide powder (particle size 1-5 μm ± 0.1 μm, hardness HV 1650 ± 30, wear resistance <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m). Co powder is used for battery materials (purity >95% ± 2%, particle size 1-3 μm ± 0.1 μm, conductivity > 10^4S /m ± 10^3S /m). The recycled WC-6Co exhibited a hardness of HV 1650 ± 30, a wear rate of 0.04 mm^3 / N · m ± 0.01 mm^3 /N · m, a cutting life of >500 h ± 50 h, and a cutting speed of >200 m/min ± 10 m/min, comparable to virgin material (deviation <2% ± 0.5%). Scanning electron microscopy (SEM) analysis revealed uniform WO_3 particles (1-5 μm ± 0.1 μm, D90/D10 <5, and particle morphology roundness >90% ± 2%), while the Co particles exhibited no agglomeration (surface roughness Ra <0.1 μm ± 0.01 μm, and uniformity >95% ± 2%). XRD analysis confirmed that the WO_3 crystal phase purity was >99% ± 0.5% (full width at half

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maximum <0.2° ± 0.02°), and the Co phase was a face-centered cubic structure (FCC, lattice constant 3.54 Å). ± 0.01 Å).

Cemented Carbide Heat Treatment and Volatile Recovery Technology - Analysis of Influencing Factors of High-Temperature Chlorination Method

Reaction temperature

At 800-1000°C ± 10°C, the recovery rate is high (>90% ± 5%). At >1100°C ± 10°C, the volatilization loss of $CoCl_2$ increases by 10% ± 2%, and WC volatilization is minimal (<0.1% ± 0.01%).

Cl_2 flow rate

When the flow rate is 10-30 L/min ± 1 L/min, the chlorination efficiency is high (>90% ± 2%); when the flow rate is <5 L/min ± 1 L/min, the recovery rate decreases by 10% ± 2% and the reaction time is extended by >20% ± 2%.

Waste particle size

When the depth is 1-10 mm ± 0.1 mm, the reaction is sufficient (penetration depth >90% ± 2%, efficiency >90% ± 2%); when the depth is >20 mm ± 0.1 mm, the efficiency drops by 10% ± 2%, and the penetration depth is <70% ± 5%.

Condensation temperature

At 100-300°C ± 5°C, WCl_6 recovery is high (>90% ± 5%); at >400°C ± 5°C, losses increase by 15% ± 3% and condensation efficiency decreases to <85% ± 2%.

Hydrolysis pH

When the pH value was 6-8 ± 0.1, the WO_3 precipitation rate was high (>95% ± 2%); when the pH value was <4 ± 0.1, the impurities increased by 10% ± 2%, and the WO_3 purity dropped to <98% ± 0.5%.

Effects of additives

When TiC/VC is <5% ± 0.5%, the reaction is normal; when it is >10% ± 0.5%, the chlorination efficiency decreases by 5% ± 1% and the by-products increase by 2% ± 0.5%.

Cemented Carbide Heat Treatment and Volatile Recovery Technology - High-Temperature Chlorination Process Optimization Suggestions

An online temperature and airflow monitoring system (accuracy ±1°C, response time <1 s, sampling frequency 1 Hz ± 0.1 Hz) was introduced to optimize the chlorination reaction efficiency (energy savings >5% ± 1%, recovery improvement 2% ± 0.5%).

A multi-stage condensation system (temperature gradient 100-300°C ± 5°C, step 50°C ± 5°C) was used to increase WCl_6 recovery to >95% ± 2% and reduce losses to <5% ± 1%.

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The Co recovery process was optimized (low-temperature volatilization at 900-1000°C ± 10°C and Ar protection flow rate increased to 10-15 L/min ± 0.5 L/min), improving the Co recovery rate to >80% ± 3%.

Using corrosion-resistant coatings (e.g. SiC or TiN, corrosion resistance >95% ± 2%, thickness 0.1-0.2 mm ± 0.01 mm) can extend the reactor life to >6000 h ± 500 h and reduce maintenance costs by 5% ± 1%.

A pre-processing classification system (based on XRF analysis, classification accuracy >98% ± 1%) was introduced to reduce additive interference and optimize resource allocation.

environmental and economic benefits

, energy consumption per ton of waste is significantly reduced (approximately 50 kWh ± 5 kWh, energy savings >10% ± 1%), CO_2 emissions are significantly reduced (approximately 0.05 t ± 0.005 t, a reduction >20% ± 2%), recycling costs are lowered, and economic benefits are improved by approximately 8% ± 1% (based on data as of 2:06 PM HKT on July 20, 2025). A life cycle assessment (LCA, according to ISO 14040) shows a 25% ± 2% reduction in carbon footprint, compliant with EU REACH regulations.

Cemented Carbide Heat Treatment and Volatile Recovery Technology-Future Development Direction of High-Temperature Chlorination Method

Develop an intelligent control system (integrated AI algorithm, control accuracy ±0.5°C, response time <0.5 s), improve recovery rate by 2%-3% ± 0.5%, and reduce manual intervention by 20% ± 2%.

Explore low-temperature chlorination technology (600-800°C ± 10°C, energy savings >15% ± 2%, energy consumption reduction of approximately 100 kWh/t ± 10 kWh/t), reducing equipment wear and maintenance costs.

Promote integration with new energy materials and use recycled Co to develop high-performance battery cathode materials (capacity >150 mAh/g ± 10 mAh/g), adding 10% ± 1% to the market value (significant annual revenue growth).

Research new catalysts (such as $FeCl_3$, addition amount 0.1%-0.5% ± 0.01%) to accelerate the chlorination reaction and shorten the reaction time by 20% ± 2%.

16.1.5.2 Cemented Carbide Heat Treatment and Volatile Recovery Technology - Vacuum Volatilization

The vacuum volatilization method separates cobalt and retains tungsten through high-temperature

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vacuum treatment. It is suitable for waste with medium to high cobalt content (Co 10%-15% ± 1%) and complex composition waste.

16.1.5.2.1 Cemented Carbide Heat Treatment and Volatile Recovery Technology - Vacuum Volatilization Process

The vacuum volatilization method includes the following detailed steps:

processed through a multi-stage crushing system. After primary crushing (jaw crusher, particle size 1-10 mm ± 0.1 mm, efficiency >95% ± 2%, pressure 50-100 MPa ± 1 MPa), it is further crushed (roller crusher, particle size distribution uniformity <5% ± 1%, specific surface area 1-2 m^2 / g ± 0.1 m^2 / g). Surface cleaning utilizes ultrasonic cleaning (frequency 40 kHz ± 2 kHz, temperature 50-60°C ± 5°C, time 15-20 min ± 1 min, power 100-150 W ± 10 W) to remove impurities, with a residual concentration of <0.1% ± 0.01% (infrared spectroscopy, accuracy ±0.005%). Drying was performed by hot air drying (100-120°C ± 5°C, 2-3 h ± 0.1 h, humidity <0.05% ± 0.01%) or vacuum drying (vacuum degree $<10^{-1}$ Pa ± 10^{-2} Pa, 80-90°C ± 5°C, 3-4 h ± 0.2 h), with strict control of moisture content.

Vacuum volatilization: The waste reaction
material is placed in a vacuum furnace (material W, temperature resistance >1200°C ± 20°C, thermal conductivity >100 W/m·K ± 10 W/m·K) and treated at 1000-1200°C ± 10°C (heating rate 5-10°C/min ± 0.5°C/min, vacuum level $<10^{-2}$ Pa ± 10^{-3} Pa , pressure control accuracy ±10^{-4} Pa) for 2-4 h ± 0.1 h. Co is volatilized (recovery rate >85% ± 5%, volatilization rate 0.1-0.2 g/min ± 0.01 g/min), while WC is retained (loss <0.1% ± 0.01%). Electromagnetic stirring (50-100 rpm ± 5 rpm) is used throughout the reaction to enhance homogeneity.

Volatile collection
Co volatiles are collected by condenser (temperature 300-500°C ± 10°C, condensation efficiency >90% ± 2%, condensation area 1-2 m^2 ± 0.1 m^2) with a recovery rate of >85% ± 5%. The residual gas is purified by a multi-stage filtration system (pore size <0.1 μm ± 0.01 μm, filtration efficiency >98% ± 1%) and a neutralization tower (NaOH solution, pH 10-12 ± 0.1), with an emission concentration of <50 mg/m^3 . ± 5 mg/ m^3 .

Tungsten recovery:
Residual WC is acid-washed (HCl concentration 1 mol/L ± 0.1 mol/L, temperature 40-50°C ± 5°C, immersion time 1-2 h ± 0.1 h, liquid-to-solid ratio 5:1 ± 0.5:1, stirring speed 100-200 rpm ± 10 rpm) to remove surface impurities (such as Fe and Ni, removal rate >95% ± 2%). The product is then rinsed with deionized water (pH 7 ± 0.2, rinses 3-5 ± 1, time 10-15 min ± 1 min) and neutralized. The purified WC has a purity >99% ± 0.5% (XRD analysis: impurities <0.1% ± 0.01%, full width at half maximum <0.2° ± 0.02°), and a particle size of 1-5 μm ± 0.1 μm.

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Cobalt recovery:

Condensed Co is purified by H_2 reduction (temperature 600-800°C ± 10°C, time 2-3 h ± 0.1 h, H_2 purity >99.999%, flow rate 5-10 L/min ± 0.5 L/min, pressure 0.1 MPa ± 0.01 MPa) to produce Co powder (purity >98% ± 0.5%, particle size 1-3 μm ± 0.1 μm, surface roughness Ra <0.1 μm ± 0.01 μm). The reduction process is equipped with uniform heating (temperature differential <±2°C), and the oxygen content is <0.01% ± 0.001%.

Quality Control and Testing:

Recovery was determined gravimetrically (accuracy ±0.5%, RSD <5%) and chemical analysis (accuracy ±1%). Co recovery was >85% ± 5%, and WC purity was >99% ± 0.5%. Impurity content was determined by ICP-MS (detection limit 0.0001% ± 0.00001%, impurities <0.01% ± 0.001%). Particle size distribution was verified by SEM (resolution <0.1 μm ± 0.01 μm) and laser particle size analysis. Performance tests included hardness (HV 1600 ± 30, load 10 kg ± 0.1 kg) and fracture toughness (10-12 $MPa·m^{1/2}$). ± 0.1 $MPa · m^{1/2}$), thermal stability (>800°C ± 20°C, TGA weight loss <1% ± 0.1%) .

16.1.5.2.2 Cemented Carbide Heat Treatment and Volatile Recovery Technology - Chemical Reaction and Mechanism of Vacuum Volatilization

The main reactions are as follows:

Cobalt volatilization

Co(s) → Co(g)

(1000-1200°C ± 10°C, vacuum <10^{-2} Pa ± 10^{-3} Pa , volatilization enthalpy ΔH_vap ≈ 380 kJ/mol ± 10 kJ/mol, volatilization rate 0.1-0.2 g/min ± 0.01 g/min)

Tungsten retention

WC(s) → no reaction

(melting point > 2800°C ± 50°C, thermal stability > 95% ± 2%, loss < 0.1% ± 0.01%)

Cobalt reduction

Co(g) + H_2 (g) → Co(s)

(600-800°C ± 10°C, ΔG < 0, approximately -10 kJ/mol ± 2 kJ/mol, recovery >85% ± 5%)

Recovery Technology - Vacuum **Volatilization Mechanism Analysis:**

At 1000-1200°C ± 10°C and a vacuum of <10^{-2}Pa ± 10^{-3}Pa , Co volatilizes (saturated vapor pressure >10^2Pa ± 10^1Pa , volatility increases exponentially with temperature), while WC is retained due to its high melting point and chemical inertness. Thermodynamic simulations show that ΔG is minimized at 1100°C (< -15 kJ/mol ± 2 kJ/mol) and the efficiency is highest (>90% ± 2%). SEM analysis reveals that the recovered WC particles are intact (morphology deviation <0.1% ± 0.02%, surface roughness Ra <0.1 μm ± 0.01 μm), and the Co powder is uniform (particle size 1-3 μm ± 0.1 μm, uniformity >95% ± 2%). XRD confirmed the WC purity to be >99% ± 0.5% (full width at half maximum <0.2° ± 0.02°), and the Co phase to be an FCC structure. Performance testing

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revealed that the recycled WCCo had a hardness of HV 1600 ± 30 and a flexural strength of 2000 MPa ± 100 MPa, with deviations of <2% ± 0.5% from the virgin material.

16.1.5.2.3 Cemented Carbide Heat Treatment and Volatile Recovery Technology - Advantages and Disadvantages of Vacuum Volatilization

Cemented Carbide Heat Treatment and Volatile Recovery Technology-Advantages of Vacuum Volatilization Method

High Co recovery
The Co recovery rate is >85% ± 5%, which is better than the high-temperature chlorination method (<75% ± 5%), thanks to the efficient volatilization under vacuum conditions.

Low waste liquid
Waste liquid discharge is <0.2% ± 0.05%, with high environmental benefits and no chemical reagent residue.

Simple process
No complex chemical reactions are required and the operating cost is low (maintenance cost <5% ± 1%).

Cemented Carbide Heat Treatment and Volatile Recovery Technology-Disadvantages of Vacuum Volatilization Method

High energy consumption
Energy consumption is >600 kWh/t ± 50 kWh/t, which is higher than the acid leaching method (<400 kWh/t ± 50 kWh/t), and the carbon footprint is approximately 0.15 t/t ± 0.01 t/t.

High equipment requirements
The vacuum system has a high investment cost (vacuum pump power 5-10 kW ± 0.5 kW, life <5000 h ± 500 h) and a short maintenance cycle.

WC Loss Risk
WC evaporates in small amounts (<0.1% ± 0.01%) at high temperatures, and may cause cumulative losses during long-term operation.

16.1.5.2.4 Cemented Carbide Heat Treatment and Volatile Recovery Technology - Application of Vacuum Volatilization

The vacuum volatilization method is suitable for scrap with medium to high cobalt content (such as WC-12Co, Co 10%-15% ± 1%, WC >85% ± 1%). The recycled WC is used for high-performance cutting tools (hardness HV 1650 ± 30, cutting life >500 h ± 50 h), and the Co is used as an alloying

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additive or battery material (purity >98% ± 0.5%, conductivity >10 ⁴ S/m ± 10 ³ S/m). The performance of recycled WC-12Co is comparable to that of virgin (hardness deviation <2% ± 0.5%, fracture toughness 10-12 MPa·m ¹ / ²) . ± 0.1 MPa · m¹ / ²), improving economic benefits by approximately 10% ± 1%. SEM analysis showed uniform WC particles (1-5 μm ± 0.1 μm, D90/D10 <5) and no agglomeration of Co powder (particle size 1-3 μm ± 0.1 μm).

Cemented Carbide Heat Treatment and Volatile Recovery Technology - Analysis of Influencing Factors of Vacuum Volatilization Method

Reaction temperature

At 1000-1200°C ± 10°C, the Co recovery rate is high (>85% ± 5%); at >1300°C ± 10°C, the WC loss increases by 5% ± 1% and the efficiency decreases by 10% ± 2%.

Vacuum degree

<10 ⁻ ² Pa ± 10 ⁻ ³ Pa, the efficiency is high (>85% ± 5%); when the pressure is >10 ⁻ ¹ Pa ± 10 ⁻ ² Pa, the recovery rate decreases by 10% ± 2% and the Co residue increases by 5% ± 1%.

Waste particle size

When the penetration depth is 1-10 mm ± 0.1 mm, the reaction is sufficient (penetration depth > 90% ± 2%); when the penetration depth is > 20 mm ± 0.1 mm, the efficiency decreases by 10% ± 2% and the reaction time is extended by > 20% ± 2%.

Condensation temperature

At 300-500°C ± 10°C, the Co recovery rate is high (>85% ± 5%); at <200°C ± 10°C, the loss increases by 10% ± 2%.

Effects of additives

When TiC/VC is <5% ± 0.5%, the impact is small; when it is >10% ± 0.5%, the Co volatilization efficiency decreases by 5% ± 1%.

Cemented Carbide Heat Treatment and Volatile Recovery Technology - Vacuum Volatilization Process Optimization Suggestions

Optimizing the vacuum system (vacuum degree <10 ⁻³ Pa ± 10 ⁻ ⁴ Pa, vacuum pump speed >1000 L/s ± 50 L/s) increased Co recovery to >90% ± 2% and reduced energy loss by >5% ± 1%.

The introduction of low-temperature volatilization technology (900-1000°C ± 10°C, energy savings >10% ± 2%, and energy consumption reduction of approximately 50 kWh/t ± 5 kWh/t) extends equipment life.

Enhanced condensation efficiency (multi-stage condensation, >95% ± 2%, condensation area increased to 2-3 m² ± 0.1 m²) , reducing Co loss <5% ± 1%.

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Applying preheating technology (200-300°C ± 10°C, preheating time 0.5-1 h ± 0.1 h) can improve the thermal responsiveness of the waste and shorten the main reaction time by 10% ± 1%.

After optimizing **the environmental and economic benefits of the cemented carbide heat treatment and volatilization recovery technology (vacuum volatilization) , energy consumption per ton of waste has been significantly reduced (approximately 50 kWh ± 5 kWh, energy savings >10% ± 1%),**
CO_2 emissions have been significantly reduced (approximately 0.04 t ± 0.005 t, a reduction >20% ± 2%), recycling costs have been reduced, and economic benefits have been improved by approximately 8% ± 1% (based on data as of 14:06 HKT on July 20, 2025). The carbon footprint has been reduced by 20% ± 2%, meeting national environmental standards.

Cemented Carbide Heat Treatment and Volatile Recovery Technology-Future Development Direction of Vacuum Volatilization Method
Developed an intelligent temperature control system (accuracy ±0.5°C, response time <0.5 s), improving recovery rates by 2%-3% ± 0.5% and optimizing energy consumption.

Explore energy-saving processes (low-temperature volatilization 900-1000°C ± 10°C, energy savings >15% ± 2%, carbon emission reduction >25% ± 2%) to reduce operating costs.

Expand to high-value applications (e.g. aerospace alloys, accuracy <0.01 mm ± 0.001 mm), adding 10% ± 1% to the market value (significant annual revenue growth).

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16.1.6 Comprehensive Comparison of Cemented Carbide Recycling Technologies

Cemented carbide recycling technologies utilize a variety of methods to recycle tungsten (WC >85% ± 1%) and cobalt (Co 6%-15% ± 1%), including chemical methods (such as zinc smelting, acid leaching, oxidation roasting and alkaline leaching), physical methods (such as mechanical crushing and sorting, arc melting), electrochemical methods (such as electrolytic dissolution and electrochemical oxidation), and thermal treatment and volatilization methods (such as high-temperature chlorination and vacuum volatilization). These technologies exhibit significant differences in recovery rate (70%-95% ± 5%), product purity (95%-99.5% ± 0.5%), energy consumption (400-1000 kWh/t ± 50 kWh/t), economic costs, and environmental impact (CO_2 emissions of 0.8-2 t CO_2 / t ± 0.2 t CO_2 / t). The selection of a recycling technology requires a comprehensive consideration of waste type, process efficiency, equipment investment, operating costs, and environmental requirements. This section provides a detailed comparison from four dimensions: recovery rate and purity, energy consumption and cost, environmental impact, and applicable waste types. Optimization suggestions are also provided based on industry trends (such as tungsten price fluctuations and recycling cost forecasts from China Tungsten Online).

16.1.6.1 Cemented Carbide Recovery Rate and Purity

Comparative Overview of Carbide Recycling Technologies

Recovery rate and purity are key indicators for evaluating the efficiency of recycling technologies and product quality. Recovery rate reflects the proportion of tungsten and cobalt extracted from scrap (target >85% ± 5%), directly impacting resource utilization. Purity determines the reusability of recycled materials (target >98% ± 0.5%) and is particularly crucial in high-precision applications such as aerospace tools and battery materials. Testing methods include chemical analysis (recovery, precision ±1%, RSD <5%, sample size 1 g ± 0.01 g), ICP-MS (purity, detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm), XRD (phase composition, scan range 10°-90°, step size 0.02° ± 0.01°, precision ±1%), and SEM (morphology, resolution <0.1 µm ± 0.01 µm, magnification 5000-10,000x). In addition, particle size distribution (laser particle size analysis, measuring range 0.01-1000 µm ± 0.05 µm) and surface roughness (Ra <0.1 µm ± 0.01 µm) are also used to evaluate product quality.

Comparison of cemented carbide recycling technologies

Zinc smelting
is a combined physical and chemical process for cemented carbide recycling. By utilizing zinc's low melting point and its interaction with cemented carbide components, it separates metal components (such as tungsten, cobalt, and nickel) from scrap cemented carbide materials, enabling resource recycling. Cemented carbide is primarily made by high-temperature sintering of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase. Due to its excellent hardness, wear resistance, and high-temperature stability, it is widely used in cutting tools, molds, and wear-

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resistant parts. However, at the end of its useful life, these scrap materials, if not recycled, result in resource waste and an environmental burden. The zinc smelting process utilizes zinc's low melting point (approximately 419.5°C) to form a low-melting-point alloy or compound with the binder phase (such as cobalt) in cemented carbide at high temperatures. Tungsten carbide, due to its high melting point (approximately 2870°C) and chemical stability, is less likely to react with it, thus achieving phase separation. The specific process involves pre-treating the cemented carbide scrap, such as mechanically crushing and cleaning to remove oil and impurities. The scrap is then mixed with zinc powder or zinc blocks in a specific ratio (typically 1:1 to 1:2), placed in an inert atmosphere (such as argon) or in a vacuum furnace, and heated to 600-1000°C. This causes the zinc to melt and penetrate the cemented carbide structure, forming a zinc-cobalt or zinc-nickel alloy with the binder phase. After heating, the zinc alloy phase is removed through cooling and mechanical separation (such as vibrating screens or centrifugation), leaving a tungsten carbide residue. Finally, cobalt and other metals are recovered from the zinc alloy through distillation (zinc boiling point is approximately 907°C) or acid leaching, while the residual zinc is processed for recycling. This method, which achieves metal separation at relatively low temperatures and avoids the complex chemical wastewater treatment required by traditional acid or alkaline leaching methods, offers advantages in environmental protection and energy efficiency. Cobalt recovery rates can reach 80%-90%, and tungsten carbide recovery rates can be optimized to 70%-85%. However, the zinc smelting method also has some limitations, such as high initial equipment investment, potential increased zinc loss and recovery costs, and low separation efficiency for complex alloy components, requiring further process optimization. Furthermore, exhaust gas and zinc vapor treatment must be strictly controlled to avoid environmental pollution. In recent years, the zinc smelting method has been improved by combining microwave heating or the addition of fluxing agents (such as borides) to increase recovery efficiency and reduce energy consumption.

WC and Co recovery rates are >90% ± 5%, with purity >99% ± 0.5%. Separation is achieved through a zinc smelting process at 800-1000°C ± 10°C, suitable for high-Co scrap (Co >10% ± 1%). Zn residue is <0.01% ± 0.001% (EDS verified, detection limit 0.001% ± 0.0001%), with a uniform particle size (1-5 µm ± 0.1 µm, D90/D10 <5).

Acid leaching achieves

Co recovery rates >95% ± 2%, WC recovery rates >85% ± 5%, and purity >99% ± 0.5%. Selective leaching using H_2SO_4 or HCl (concentration 1-2 mol/L ± 0.1 mol/L, temperature 40-60°C ± 5°C, soak time 1-2 h ± 0.1 h) achieves WC dissolution rates <0.1% ± 0.01% (XRD analysis: impurities <0.05% ± 0.01%). Fe/Ni impurities <0.01% ± 0.001% (ICP-MS). Suitable for medium- and low-cobalt waste (Co 6%-10% ± 1%).

Oxidation roasting alkaline leaching

Oxidation roasting and alkaline leaching is a cemented carbide recycling technology that combines thermochemical and hydrochemical processes. It aims to efficiently extract metal components, such as tungsten, cobalt, and nickel, from scrap cemented carbide materials, achieving resource recycling. Cemented carbide is primarily made by high-temperature sintering of tungsten carbide (WC) as a

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hard phase and cobalt (Co) or nickel (Ni) as a binder phase. Due to its exceptional hardness, wear resistance, and high-temperature stability, it is widely used in cutting tools, molds, and wear-resistant components. However, at the end of its useful life, if these scrap materials are not recycled, they lead to resource waste and environmental pressure. The core principle of the oxidation roasting and alkaline leaching method is to oxidize the tungsten carbide in the cemented carbide into tungsten oxide (WO_3) through high-temperature oxidation roasting . This is then dissolved in an alkaline solution (such as sodium hydroxide, NaOH) into soluble tungstates (such as sodium tungstate, Na_2WO_4) . The binder metal is partially dissolved or remains, allowing for graded recovery. The specific process involves pre-treating the scrap carbide, such as mechanically crushing and cleaning to remove oil and impurities. The pre-treated material is then placed in a roasting furnace and heated to 600-800°C in an air or oxygen atmosphere for several hours to oxidize the tungsten carbide to WO_3 and partially oxidize the binder metal (such as cobalt) to oxides (such as CoO). After roasting, the oxidation product is mixed with a NaOH solution and subjected to an alkaline leaching reaction at 100-200°C and 1-2 MPa. The tungstate dissolves into the solution, while the cobalt oxide and other residues are separated by filtration. Next, high-purity tungsten compounds (such as ammonium metatungstate) are recovered from the solution through methods such as acidification, ion exchange, or evaporative crystallization. The residue can then be further extracted with acid leaching or electrochemical methods to extract cobalt or nickel. Finally, the resulting wastewater is neutralized to meet environmental protection requirements. This method offers significant advantages in tungsten resource recovery due to its efficient oxidation and dissolution of tungsten carbide, with a tungsten recovery rate of 85%-95%. It is particularly suitable for major tungsten producing countries such as China. In addition, oxidative roasting and alkaline leaching are also relatively effective for recovering binder metals, with cobalt recoveries reaching 60%-80%. Energy consumption can be reduced by optimizing roasting conditions. However, this method also presents challenges, such as the high energy input required for the roasting process, high equipment investment and operating costs, and the need for strict control of waste gases (such as CO_2) and waste alkali treatment to avoid environmental pollution. In recent years, oxidative roasting and alkaline leaching methods have been improved by combining them with microwave heating or catalyst-assisted technologies to increase efficiency and reduce environmental impact.

Tungsten recovery rates are >85% ± 5%, Co recovery rates are <80% ± 5%, and WO_3 purity is >99% ± 0.5%. After oxidation at 600-800°C ± 10°C, leaching is performed using a NaOH solution (concentration 2-4 mol/L ± 0.1 mol/L, temperature 80-100°C ± 5°C, time 2-3 h ± 0.1 h). Suitable for complex waste materials (TiC/VC additives <5% ± 0.5%). TiC residue is <0.05% ± 0.01% (SEM observation), and particle morphology retention is >90% ± 2%.

Mechanical crushing and sorting

Mechanical crushing and sorting is a physical method used to pre-treat and initially separate scrap cemented carbide materials during cemented carbide recycling, in order to achieve the effective recovery of metal components (such as tungsten, cobalt, and nickel). Cemented carbide is mainly made of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase through high-temperature sintering. Due to its excellent hardness, wear resistance, and high-

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temperature performance, it is widely used in cutting tools, molds, and wear-resistant parts. However, as the service life ends, if these waste materials are not recycled, it will lead to resource waste and environmental burden. The core of the mechanical crushing and sorting method is to use mechanical force to break the scrap cemented carbide into small particles, and sort them by physical properties (such as density, particle size, and magnetism) to separate different components, providing a basis for subsequent chemical or metallurgical recycling processes. The specific process involves pre-treating the carbide scrap, such as cleaning to remove surface oil, paint, or adhesions to improve crushing efficiency. The scrap is then mechanically crushed using crushing equipment (such as a jaw crusher, hammer crusher, or ball mill), typically controlling the particle size to within a range of 0.1-5 mm to ensure operability for subsequent sorting. Separation is then achieved using sorting techniques such as gravity separation (using density differences to separate tungsten carbide and binder phases via a shaker or wind-driven classification), magnetic separation (using the magnetic properties of cobalt to separate the cobalt-containing fraction from the non-magnetic tungsten carbide), or screening (classification based on particle size). Finally, the sorted components (such as the tungsten-rich and cobalt-rich fractions) are collected for further processing, such as acid leaching, alkaline leaching, or smelting recovery. This dry process, which does not involve chemical reagents, offers advantages such as environmental friendliness, relatively low energy consumption, and simple equipment operation. It is particularly suitable for processing large quantities of scrap tools or abrasives. The initial separation rate of tungsten carbide and binder phase can reach 70%-90%, depending on the uniformity of the scrap and the accuracy of the sorting equipment. However, mechanical crushing and sorting methods also have limitations. For example, the separation efficiency of complex multiphase alloys is low, fine particles may cause losses, and the dust generated during the crushing process needs to be equipped with dust removal equipment to reduce environmental impact. In addition, it is impossible to fully achieve high-purity recovery of metals and needs to be improved in combination with subsequent wet or fire processes. In recent years, combined with ultrasonic-assisted crushing or intelligent sorting technology (such as X-ray sorting), mechanical crushing and sorting methods are being optimized to improve recovery efficiency and accuracy. Overall, this method, as an important pretreatment link in the cemented carbide recycling process, has significant value in resource conservation and industrial production.

Recovery rate >80% ± 5%, purity >98% ± 0.5%. Using a jaw crusher (particle size 1-10 mm ± 0.1 mm, efficiency >95% ± 2%) and magnetic separation (magnetic field strength 0.5-1 T ± 0.1 T), suitable for simple waste materials (additives <2% ± 0.5%). Impurities (Fe, Si) <0.05% ± 0.01% (EDS analysis), particle size distribution uniformity <5% ± 1%.

Arc melting method

Arc melting is a metallurgical recycling process that utilizes high-temperature arc energy to melt and separate cemented carbide scrap. It aims to extract metal components (such as tungsten, cobalt, and nickel) from scrap cemented carbide materials, thereby achieving resource recycling. Cemented carbide is primarily manufactured by high-temperature sintering of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase. Due to its excellent hardness, wear resistance, and high-temperature stability, it is widely used in cutting tools, molds, and wear-resistant components. However, at the end of its useful life, if these scrap materials are not recycled, they lead to resource waste and environmental burdens. The core principle of arc melting is to use a DC or AC arc to generate high temperatures of up to 2000-3000°C in an inert atmosphere (such as argon) or a vacuum environment to melt the cemented carbide scrap. The binder metal (such as cobalt) melts and separates first due to its lower melting point (approximately 1495°C), while the tungsten carbide, due to its higher melting point (approximately 2870°C), remains partially or exists as an oxide, thus achieving compositional fractionation. The specific process involves pre-treating the cemented carbide scrap, such as mechanically crushing and cleaning to remove oil and impurities to improve smelting efficiency. The pre-treated scrap is then placed in an electric arc furnace, where electrodes (such as graphite electrodes) generate arc heating via high voltage to melt the scrap. The smelting time (typically 30 minutes to 2 hours) and current (100-500A) are controlled to optimize separation. During the smelting process, the molten binder metal settles to the bottom of the furnace, forming molten metal, while tungsten carbide residue floats to the surface. After cooling, the molten metal and residue are collected by mechanical separation or dumping. The molten metal can be further refined to recover high-purity cobalt or nickel, while the residue can be used to extract tungsten through acid or alkaline leaching. Finally, the resulting slag and exhaust gas are treated to meet environmental standards. This method has high industrial potential due to its ability to process large quantities of scrap in one go, achieving cobalt recovery rates of 85%-95% and, through optimization, tungsten recovery rates of 60%-80%. Its adaptability to complex alloy compositions also makes it highly adaptable to industrial applications. However, arc melting also has limitations, such as high equipment investment and operating costs (due to the need for a dedicated arc furnace and inert gas), high energy consumption, and the potential generation of small amounts of hazardous gases (such as CO) during the melting process, necessitating an exhaust gas treatment system. Furthermore, tungsten carbide loss and slag disposal still require further technical improvements. In recent years, arc melting has been optimized by combining it with plasma-assisted or microwave preheating techniques to reduce energy consumption and improve recovery rates.

Recovery rate >80% ± 5%, purity >98% ± 0.5%. Melting of high hardness scrap (HV >1800 ± 30) at 2000-2500°C ± 50°C (current 500-1000 A ± 50 A, voltage 20-40 V ± 2 V), oxygen content <0.01% ± 0.001% (TGA measurement, weight loss <0.1% ± 0.01%), suitable for high density scrap (density >14 g/cm^3) . ± 0.1 g/cm^3) .

Electrolytic dissolution method

Electrolytic dissolution method is a recycling process that uses the principle of electrochemical reaction to extract metal components (such as tungsten, cobalt and nickel) from cemented carbide scrap, and is widely used in the field of resource recycling. Cemented carbide is mainly made of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a bonding phase through high-temperature sintering. Due to its excellent hardness, wear resistance and high-temperature stability, it is widely used in cutting tools, molds and wear-resistant parts. However, with the end of its service life, if these scraps are not recycled, it will lead to resource waste and environmental pressure. The core of the electrolytic dissolution method is to apply an electric field in the electrolyte solution to make the scrap cemented carbide as an electrode undergo selective oxidation or reduction

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reaction, thereby dissolving and separating the metal components. The specific process includes: first, pre-treating the scrap carbide, such as mechanical crushing and cleaning to remove oil and impurities to ensure surface cleanliness and reaction efficiency; then placing the scrap as the anode in an electrolytic cell, the electrolyte is usually an aqueous solution containing sulfuric acid (H_2SO_4) or sodium chloride (NaCl), and the cathode is made of inert materials (such as graphite or titanium). A constant voltage (generally 1-6V) and current density (0.1-2 A/cm²) are applied , and the reaction temperature is controlled at 20-60°C; in this process, the binder phase metal (such as cobalt) is preferentially oxidized and dissolved into metal ions (such as Co^{2+}) enters the solution, while tungsten carbide, due to its chemical stability and low solubility, is partially retained or requires further treatment. After the electrolysis is completed, the electrolyte containing metal ions and the undissolved tungsten carbide residue are separated by filtration. Subsequently, high-purity metals (such as cobalt salts or tungstates) are recovered from the solution through precipitation (such as adding sodium hydroxide to produce cobalt hydroxide), solvent extraction, or electrolysis. The residue can then be used to extract tungsten through alkaline or acid leaching. Finally, the electrolysis wastewater is neutralized to meet environmental requirements. This method offers certain environmental advantages due to its high selectivity, relatively controllable energy consumption, and avoidance of the large amounts of chemical waste generated by traditional acid or alkaline leaching. Cobalt recovery rates can reach 75%-90%, and tungsten recovery rates can be optimized to 50%-70%. However, electrolytic dissolution also has some limitations, such as high initial equipment investment and the need for precise control of electrolysis parameters to avoid side reactions and electrode loss. It is suitable for small- to medium-scale waste recovery, and its efficiency in processing complex multiphase alloys may be limited. In addition, the electrolysis process may produce small amounts of gases (such as chlorine or oxygen), requiring a ventilation system. In recent years, the electrolytic dissolution method is being improved by combining pulsed electric field or ultrasound-assisted technology to increase the recovery rate and reduce energy consumption.

Co recovery rate>90% ± 5%, WC recovery rate>85% ± 5%, purity>99% ± 0.5%. At 50-200 A/ m² Operating at a current density of ± 10 A/ m² and an electrolyte (H_2SO_4 1-2 mol/L ± 0.1 mol/L) at 20-40°C ± 5°C, this system is suitable for low- to medium-cobalt waste (Co 6%-10% ± 1%). Impurities are <0.01% ± 0.001% (ICP-MS), and conductivity is >10^4S / m ± 10^3S /m.

Electrochemical oxidation

is a recycling process that uses electrochemical reactions to extract metal components (such as tungsten, cobalt, and nickel) from cemented carbide scrap . This process achieves selective oxidation separation by applying an electric field in an electrolyte solution, making it widely used in resource recycling. Cemented carbide is primarily made of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase, sintered at high temperatures. Due to its excellent hardness, wear resistance, and high-temperature stability, it is widely used in cutting tools, molds, and wear-resistant parts. However, at the end of its useful life, if these scrap materials are not recycled, they result in resource waste and an environmental burden. The core of the electrochemical oxidation process is to use the cemented carbide scrap as the anode. An applied potential in the electrolyte

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solution promotes oxidative dissolution of the metals, while the tungsten carbide, due to its chemical stability and low solubility, is partially retained, thus achieving component separation. The specific process flow includes: first , pre-treating the scrap cemented carbide, such as mechanical crushing and cleaning to remove oil and impurities to increase the reaction surface area and efficiency; then placing the scrap as the anode in the electrolytic cell, the electrolyte is usually an aqueous solution containing sulfuric acid (H_2SO_4) , nitric acid (HNO_3) or sodium chloride (NaCl), and the cathode is made of inert materials (such as graphite or platinum), applying a constant voltage (generally 2-6V) and current density (0.1-1.5 A/cm^2) , and the reaction temperature is controlled at 20-70°C; in this process, the binder phase metal (such as cobalt) is oxidized to generate soluble ions (such as Co^{2+}) that enter the solution, while tungsten carbide may be partially oxidized to tungsten oxide (WO_3) or remains in a solid phase. After electrolysis, the electrolyte containing metal ions and the undissolved residue are separated by filtration. Subsequently, high-purity metals (such as cobalt salts) are recovered from the solution through precipitation (such as adding NaOH to produce cobalt hydroxide), solvent extraction, or electrolysis. The residue can be further extracted for tungsten through alkaline or acid leaching. Finally, the electrolytic wastewater is neutralized to meet environmental standards. This method offers certain environmental and efficiency advantages due to its strong selective oxidation ability, relatively controllable energy consumption, and the reduction of the large amount of chemical reagents used in traditional wet processes. Cobalt recovery rates can reach 80%-90%, and tungsten recovery rates can reach 60%-75% through optimization. However, electrochemical oxidation methods also have some challenges, such as high initial equipment investment and the need for precise control of electrolysis parameters (such as voltage and current) to avoid over-oxidation or electrode corrosion. It is suitable for small- to medium-scale waste treatment, and the separation efficiency of complex multiphase alloys may be limited. In addition, small amounts of gases (such as oxygen or chlorine) may be generated during the electrolysis process, requiring appropriate ventilation and waste gas treatment systems. In recent years, electrochemical oxidation methods are being improved by combining pulsed electric fields or adding catalyst technology to increase recovery rates, reduce energy consumption and optimize process stability.

Tungsten recovery rate>85% ± 5%, Co recovery rate<80% ± 5%, WO_3 purity >99% ± 0.5%. At 50-100 A/ m^2 Electrolytic treatment at a current density of ± 5 A/ m^2 and a temperature of 60-80°C ± 5°C is suitable for complex waste materials (TiC/VC <5% ± 0.5%). Residual carbon is <0.05% ± 0.01% (XRD analysis), and the morphology is porous (pore size <1 μm ± 0.1 μm).

High-temperature chlorination

The high-temperature chlorination process is a recycling process that extracts metal components (such as tungsten, cobalt, and nickel) from cemented carbide scrap through a high-temperature chlorination reaction. Combining thermochemistry and gas-solid reaction principles, it is widely used in resource recycling. Cemented carbide is primarily made of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase through high-temperature sintering. Due to its excellent hardness, wear resistance, and high-temperature stability, it is widely used in cutting tools, molds, and wear-resistant parts. However, at the end of its useful life, if these scrap materials

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are not recycled, they will lead to resource waste and environmental pressure. The core of the high-temperature chlorination process is to use chlorine gas (Cl_2) or a chlorinating agent (such as calcium chloride ($CaCl_2$)) to react with the metals in the cemented carbide under high temperature conditions, forming volatile or soluble chlorides (such as $WOCl_4$ and $CoCl_2$), which can then be separated and extracted. The specific process involves pre-treating the cemented carbide scrap, such as mechanically crushing and cleaning to remove oil and impurities to increase the reaction surface area. The pre-treated scrap is then placed in a reactor where chlorine gas is introduced and heated to 500-1000°C in an inert atmosphere (such as argon) or a controlled oxidizing environment. The reaction typically lasts 1-4 hours. The chlorine reacts with tungsten carbide to produce tungsten dichloride pentoxide ($WOCl_4$, boiling point approximately 91°C), while the binder metal (such as cobalt) produces cobalt chloride ($CoCl_2$, melting point approximately 740°C). During the reaction, volatile chlorides are carried by the gas flow to a condenser for condensation and recovery, and the residue (such as unreacted carbon) is separated by filtration. Tungsten and cobalt compounds are then separated and purified from the condensate by distillation or solvent extraction, and the residue can be further processed to recover other metals. Finally, the generated waste gases (such as unreacted Cl_2) are treated by absorption (e.g., neutralization with NaOH solution) to meet environmental protection requirements. This method has high potential for industrialization due to its ability to efficiently decompose tungsten carbide and binder metal, achieving tungsten recovery rates of 80%-90 % and cobalt recovery rates of 75%-85%, and its strong adaptability to complex multiphase alloys. However, the high-temperature chlorination method also has some limitations, such as high equipment requirements (corrosion-resistant reactors and exhaust gas treatment systems are required), high energy consumption, high costs for chlorine use and exhaust gas treatment, and certain safety risks during operation (such as chlorine leaks). In addition, the chlorination reaction may produce small amounts of harmful byproducts, requiring strict control of process parameters. In recent years, the high-temperature chlorination method is being optimized by combining it with microwave heating or catalyst-assisted technologies (such as $FeCl_3$) to reduce energy consumption, improve recovery rates, and minimize environmental impact.

Tungsten recovery >90% ± 5%, Co recovery <75% ± 5%, WO_3 purity >99% ± 0.5%. Operate at 800-1000°C ± 10°C and a Cl_2 flow rate of 10-30 L/min ± 1 L/min, suitable for high-tungsten scrap (WC >90% ± 1%). Residual Cl_2 is <0.01% ± 0.001% (verified by EDS), and particle size is 1-5 µm ± 0.1 µm.

Vacuum evaporation method

Vacuum volatilization is a physical-chemical recovery process that separates and recovers metal components (such as tungsten, cobalt, and nickel) from cemented carbide scrap by exploiting the volatility differences between metals or compounds under vacuum conditions. It is widely used in resource recycling. Cemented carbide is primarily made by high-temperature sintering of tungsten carbide (WC) as a hard phase and cobalt (Co) or nickel (Ni) as a binder phase. Due to its excellent hardness, wear resistance, and high-temperature stability, it is widely used in cutting tools, molds, and wear-resistant parts. However, at the end of its useful life, if these scrap materials are not recycled, they lead to resource waste and environmental burdens. The core principle of vacuum

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volatilization is to use the vacuum environment to lower the boiling point of volatile substances. High-temperature heating causes the binder phase metal (such as cobalt) or its compounds to volatilize preferentially, while the tungsten carbide, due to its high melting point (approximately 2870°C) and low volatility, remains, thus achieving component separation. The specific process flow includes: first, pre-treating the scrap cemented carbide, such as mechanical crushing and cleaning to remove oil and impurities to improve heating efficiency; then, placing the pre-treated scrap in a vacuum furnace, evacuating it to a low-pressure environment (typically 10^{-2} to 10^{-5} Pa) , and heating it to 1000-1500°C for a reaction time of 2-6 hours. During this process, the binder metal (such as cobalt, melting point 1495°C) or its oxide/chloride volatilizes under vacuum conditions and condenses in a condenser, while tungsten carbide remains in the furnace. After condensation, the volatiles are separated and recovered through mechanical collection or chemical treatment (such as acid leaching) to obtain high-purity cobalt or nickel. The residue can be used to extract tungsten through subsequent alkaline or acid leaching. Finally, the vacuum pump exhaust is treated to remove trace volatiles to meet environmental protection requirements. Because this method avoids the use of chemical reagents and is a dry process, it has the advantages of high environmental protection and high product purity. The cobalt recovery rate can reach 70%-90%, and the tungsten recovery rate can reach 60%-80% through optimization. It is also highly adaptable to complex multiphase alloys. However, the vacuum volatilization method also has some limitations, such as high equipment investment and operating costs (vacuum furnaces and precision control systems are required), high energy consumption, and is only suitable for small and medium-scale waste recycling. The volatilization process also requires strict control of temperature and vacuum degree, and slight deviations may affect the recovery efficiency. In addition, there may be certain losses during the condensation and collection process of volatiles. In recent years, the vacuum volatilization method is being improved by combining microwave heating or the addition of volatilizers (such as chlorides) to reduce energy consumption, increase recovery rates, and optimize process stability.

Co recovery >85% ± 5%, WC recovery >80% ± 5%, purity >98% ± 0.5%. Volatilization at 1000-1200°C ± 10°C and vacuum <10^{-2} Pa ± 10^{-3} Pa , suitable for high-Co scrap (Co >10% ± 1%). Oxygen content <0.01 % ± 0.001% (EDS), particle uniformity >95% ± 2%.

Comparative Analysis Table of Cemented Carbide Recycling Methods

A comparative analysis of cemented carbide recovery methods (acid leaching, alkaline leaching, electrochemical method, zinc melting, oxidation roasting alkaline leaching, mechanical crushing and sorting, arc melting, electrolytic dissolution, electrochemical oxidation, high-temperature chlorination, and vacuum volatilization) lists their principles, advantages, disadvantages, recovery rates, applicable scenarios, and process characteristics to help understand the applicability and limitations of each method.

method	principle	advantage	shortcoming	Recovery rate (tungsten/cobalt)	Applicable Scenarios	Process characteristics
Acid leaching	Acid (such as	Simple process, low	WC recovery rate	60-70% / 70-80%	Small-scale	Wet process,

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method	principle	advantage	shortcoming	Recovery rate (tungsten/cobalt)	Applicable Scenarios	Process characteristics
	H_2SO_4) dissolves the binder phase and separates WC	equipment requirements, and efficient Co recovery	is low (60-70%), and waste liquid treatment is difficult		waste tool recycling	producing acidic waste liquid
Alkali leaching	Alkali (such as NaOH) dissolves WC at high temperature to form tungstate	High WC recovery rate (80-90%), partial recovery of Co	High temperature and high pressure requirements, complex waste alkali solution treatment	80-90% / 50-60%	Large-scale tungsten resource recovery	Wet process + high temperature, great environmental challenges
Electrochemical method	Electrolytic dissolution of Co, partial retention of WC	High selectivity, good environmental protection, efficient Co recovery	High equipment investment and difficult parameter control	70-90% / 60-80%	Small and medium-sized waste treatment	Wet process + electrochemical process, waste gas needs to be treated
Zinc melting method	Zinc melt infiltration, separation of Co and WC	Good environmental protection, high Co recovery rate (80-90%)	High equipment cost and large zinc loss	70-85% / 80-90%	Large-scale waste tool recycling	Dry process + smelting, zinc recovery cycle required
Oxidation roasting alkaline leaching	Calcination and oxidation of WC to WO_3 , alkali leaching and dissolution	High WC recovery rate (85-95%), partial recovery of Co	High energy consumption and complex waste gas and waste liquid treatment	85-95% / 60-80%	Complex multiphase waste recycling	Dry method + wet method, the process is more complicated
Mechanical crushing and sorting	Physical crushing + density/magnetic separation	Environmentally friendly, low cost, efficient pretreatment	Low separation purity, requiring subsequent processing	70-90% (preliminary)	Batch preprocessing	Dry method, dust needs to be controlled
Arc melting method	Arc high temperature melting, separation of Co and WC	Large-scale processing, high Co recovery rate (85-95%)	High energy consumption and high equipment investment	60-80% / 85-95%	Industrial large-scale recycling	Dry process + smelting, inert atmosphere required
Electrolytic dissolution	Electrolytic oxidation of Co, partial retention of WC	Environmentally friendly, high Co recovery rate (75-90%)	High equipment cost and strict parameter control	50-70% / 75-90%	Small and medium-sized waste treatment	Wet method + electrochemical method, waste liquid needs to be treated
Electrochemical	Electrochemical	Strong selectivity	High equipment	60-75% / 80-90%	Small and	Wet process +

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method	principle	advantage	shortcoming	Recovery rate (tungsten/cobalt)	Applicable Scenarios	Process characteristics
oxidation method	oxidation of Co, partial retention of WC	and good environmental protection	investment and difficult parameter control		medium-sized waste recycling	electrochemical process, waste gas needs to be treated
High-temperature chlorination	Chlorine reacts at high temperature to form volatile chlorides	High WC and Co recovery rate (80-90%)	High safety risks and complex waste gas treatment	80-90% / 75-85%	Complex alloy recycling	Dry process + gas phase, corrosion-resistant equipment is required
Vacuum evaporation method	Co is volatilized at high temperature in vacuum, while WC is retained	Environmentally friendly, high product purity	High equipment cost and high energy demand	60-80% / 70-90%	Small and medium-sized waste recycling	Dry method + vacuum, requires precise control

Comparative Analysis of Cemented Carbide Recovery Methods

Principle Differences

Wet methods (such as acid leaching and alkaline leaching) rely on chemical dissolution and are suitable for targeted extraction.

Dry methods (such as zinc melting and arc melting) use physical melting or volatilization and are suitable for large-scale processing.

Electrochemical methods (such as electrolytic dissolution and electrochemical oxidation) combine electric fields and chemical reactions, emphasizing selectivity.

Recovery rate

The highest WC recovery rate is achieved by oxidation roasting and alkaline leaching (85-95%), and the highest Co recovery rate is achieved by arc melting and zinc melting (85-95%).

Mechanical crushing and sorting as pretreatment have low recovery rates and require subsequent process support.

Advantages and applicability

The more environmentally friendly methods include mechanical crushing and sorting, vacuum volatilization and electrochemical methods, which are suitable for green recycling needs.

Arc melting and zinc melting methods are suitable for large-scale industrialization, while electrochemical methods and vacuum volatilization methods are suitable for small and medium-sized scales.

Complex alloy recovery is suitable for high-temperature chlorination and oxidation roasting alkaline leaching methods.

Disadvantages and Challenges

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Methods that require high energy consumption and large equipment investment include arc melting, high-temperature chlorination and vacuum volatilization.
The problem of waste liquid or waste gas treatment is a common bottleneck of acid leaching, alkaline leaching and high-temperature chlorination methods.
The difficulty in parameter control is a limitation of the electrochemical method and vacuum volatilization method.

Process characteristics
Wet processes (such as acid leaching and alkaline leaching) produce waste liquid and require environmental protection facilities.
Dry processes (such as arc melting and vacuum volatilization) require inert atmosphere or vacuum conditions and complex equipment.
Combined processes (such as oxidation roasting and alkaline leaching) integrate dry and wet methods, which are highly efficient but have a long process.

Comprehensive Recommendations

Selection basis
Select a method based on the waste size, composition complexity, and environmental requirements. For small-scale recycling, electrochemical or mechanical crushing and sorting are preferred; for large-scale industrialization, arc melting or zinc smelting are recommended; for high tungsten recovery requirements, oxidative roasting and alkaline leaching are preferred.

Optimization direction
Incorporate modern technologies (such as microwave heating and ultrasonic assistance) to improve efficiency and strengthen waste treatment technology to reduce environmental impact.

Current Trends
The industry tends to develop green and low-cost processes, and electrochemical and vacuum volatilization methods are attracting attention due to their environmental friendliness.

16.1.6.2 Energy Consumption and Cost of Cemented Carbide Recycling

Energy Consumption and Cost Comparison Overview:
Energy consumption and cost are key to technical feasibility, encompassing equipment investment (estimated USD 500,000-3 million ± USD 100,000), operating costs (including electricity, reagents, and maintenance), and the added value of recycled materials. Energy consumption figures are based on 400-1000 kWh/t ± 50 kWh/t, and cost estimates are based on 2025 market trends from China Tungsten Online (tungsten prices of USD 200-300 ± USD 20/t, and Co prices of USD 30-50 ± USD 5/kg).

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Comparison of cemented carbide recycling technologies

Zinc melting method

Energy consumption is 600-800 kWh/t ± 50 kWh/t, equipment investment is estimated at USD 1.5-2 million ± 100,000, operating costs are medium to high (Zn consumables account for approximately 20% ± 2%), and added value is high (purity >99% ± 0.5%).

Acid leaching

Energy consumption is 500-700 kWh/t ± 50 kWh/t, equipment investment is USD 1-1.5 million ± 100,000, operating costs are moderate (acid recycling rate > 90% ± 2%), and added value is high.

Oxidation roasting alkaline leaching

Energy consumption is 700-900 kWh/t ± 50 kWh/t, equipment investment is 1.2-1.8 million USD ± 100,000 USD, operating costs are relatively high (NaOH consumption is 0.5-1 kg/t ± 0.1 kg/t), and the added value is medium.

Mechanical crushing and sorting

Energy consumption is 400-500 kWh/t ± 50 kWh/t, equipment investment is USD 500,000-1,000,000 ± 100,000, with the lowest operating cost (maintenance fee <5% ± 1%) and low added value.

Arc melting method

Energy consumption: 800-1000 kWh/t ± 50 kWh/t, equipment investment: 2-3 million USD ± 100,000 USD, high operating costs (electric arc furnace power consumption > 50% ± 2%), medium added value.

Electrolytic dissolution

Energy consumption is 600-800 kWh/t ± 50 kWh/t, equipment investment is 1.5-2 million USD ± 100,000 USD, operating costs are moderate (electrolyte recovery rate >85% ± 2%), and added value is high.

Electrochemical oxidation method

Energy consumption is 700-900 kWh/t ± 50 kWh/t, equipment investment is 1.2-1.8 million USD ± 100,000 USD, operating costs are relatively high (electrode loss is 5-10% ± 1%), and the added value is medium.

High-temperature chlorination

Energy consumption is 800-1000 kWh/t ± 50 kWh/t, equipment investment is 1.5-2 million USD ± 100,000 USD, operating costs are high (Cl_2 consumption is 0.1-0.2 kg/t ± 0.01 kg/t), and added value is high.

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Vacuum evaporation method

Energy consumption: 900-1000 kWh/t ± 50 kWh/t; equipment investment: 2-2.5 million USD ± 100,000 USD; operating costs are high (vacuum pump maintenance: 10-15% ± 2%); and the added value is moderate.

16.1.6.3 Environmental Impact of Cemented Carbide Recycling

Environmental impact comparison overview

Environmental impact includes CO_2 emissions (0.8-2 t CO_2 / t ± 0.2 t CO_2 / t), waste liquid discharge (<0.2%-2% ± 0.05%), waste gas concentration (<50-200 mg/ m^3 ± 5 mg/m^3) and resource consumption (5-20 m^3/t ± 1 m^3/t of water) . Assessment is based on ISO 14040 Life Cycle Analysis (LCA) and the national standard GB 8978-1996.

Comparison of cemented carbide recycling technologies

Zinc melting method

CO_2 emissions: 1-1.5 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid <0.2% ± 0.05 % , waste gas <50 mg/ m^3 ± 5 mg/m^3 , water consumption 5-10 m^3 /t ± 1 m^3 /t.

Acid leaching

CO_2 emissions : 0.8-1.2 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid: 1%-2% ± 0.05%, waste gas: <100 mg/ m^3 ± 5 mg/m^3 , water consumption 10-15 m^3 /t ± 1 m^3 /t.

Oxidation roasting alkaline leaching

CO_2 emissions: 1.2-1.8 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid: 0.5%-1% ± 0.05%, waste gas: <150 mg / m^3 ± 5 mg/m^3 , water consumption 15-20 m^3 /t ± 1 m^3 /t.

Mechanical crushing and sorting

CO_2 emissions: 0.8-1 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid <0.1% ± 0.01 % , waste gas <50 mg/ m^3 ± 5 mg/m^3 , water consumption 5-10 m^3 /t ± 1 m^3 /t.

Arc melting method

CO_2 emissions: 1.5-2 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid <0.1% ± 0.01 % , waste gas <200 mg/ m^3 ± 5 mg/m^3 , water consumption 5-10 m^3 /t ± 1 m^3 /t.

Electrolytic dissolution

CO_2 emissions: 1-1.5 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid: 1%-2% ± 0.05 % , waste gas: <100 mg/ m^3 ± 5 mg/m^3 , water consumption 10-15 m^3 /t ± 1 m^3 /t.

Electrochemical oxidation method

CO_2 emissions: 1.2-1.8 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid: 0.5%-1% ± 0.05%, waste gas: <150 mg / m^3 ± 5 mg/m^3 , water consumption 15-20 m^3 /t ± 1 m^3 /t.

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High-temperature chlorination

CO_2 emissions: 1.5-2 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid <0.2% ± 0.05 % , waste gas <100 mg/ m^3 ± 5 mg/m^3 , water consumption 5-10 m^3 /t ± 1 m^3 /t.

Vacuum evaporation method

CO_2 emissions: 1.5-2 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid <0.1% ± 0.01 % , waste gas <50 mg/ m^3 ± 5 mg/m^3 , water consumption 5-10 m^3 /t ± 1 m^3 /t.

Analysis and Summary

Environmental impact

Mechanical sorting and zinc smelting methods have the smallest environmental impact (CO_2 < 1.5 t CO_2 / t ± 0.2 t CO_2 / t, waste liquid <0.2% ± 0.05%), while arc melting and vacuum volatilization methods have the greatest impact (CO_2 > 1.5 t CO_2 / t ± 0.2 t CO_2 / t).

Influencing factors

Energy consumption ratio (50%-70% ± 5%), exhaust gas treatment efficiency (>98% ± 1%) and water recycling rate (>90% ± 2%) are the main variables.

Optimization suggestions

Promote low-carbon energy (such as solar energy, emission reduction >20% ± 2%) and exhaust gas absorption system (NaOH neutralization, efficiency >95% ± 1%) to reduce CO_2 emissions to <1 t CO_2 / t ± 0.2 t CO_2 / t.

16.1.6.4 Types of scrap suitable for cemented carbide recycling

Comparative overview of applicable scrap types

Scrap types include high Co scrap (Co >10% ± 1%), medium and low Co scrap (Co 6%-10% ± 1%), complex scrap (additive TiC/VC <5% ± 0.5%) and simple scrap (additive <2% ± 0.5%), which affect the technical applicability.

Comparison of cemented carbide recycling technologies

Zinc melting method : high Co scrap, adaptability >90% ± 2%.
Acid leaching method : medium and low Co waste, adaptability >95% ± 2%.
Oxidation roasting and alkaline leaching method : complex waste, adaptability >85% ± 2%.
Mechanical crushing and sorting : simple waste, adaptability >90% ± 2%.
Arc melting method : high hardness scrap, adaptability >80% ± 2%.
Electrolytic dissolution method : medium and low Co waste, adaptability >90% ± 2%.
Electrochemical oxidation method : complex waste, adaptability >85% ± 2%.
High temperature chlorination method : high tungsten waste, adaptability >90% ± 2%.
Vacuum volatilization method : high Co waste, adaptability >85% ± 2%.

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Analysis and Summary

applicability

Zinc melting and vacuum volatilization are suitable for high-Co waste, acid leaching and electrolytic dissolution are better than medium- and low-Co waste, and oxidation roasting alkali leaching and electrochemical oxidation are suitable for complex waste.

Optimization suggestions

Sorting waste materials through XRF pre-analysis (accuracy ±0.1%), matching the best technology, and improving overall adaptability to >90% ± 2%.

Comparison table of cemented carbide recovery rate and purity

technology	Recovery rate (%)	purity(%)	Features and Remarks
Zinc melting method	WC/Co >90 ± 5	>99 ± 0.5	Applicable to high Co scrap (Co>10%±1%), Zn residue <0.01%±0.001% (EDS verification), high recovery rate, suitable for WC-Co scrap.
Acid leaching	Co >95 ± 2, WC >85 ± 5	>99 ± 0.5	High selectivity (WC dissolution rate <0.1%±0.01%), Fe/Ni impurities <0.01%±0.001%, suitable for high-purity Co recovery.
Oxidation roasting alkaline leaching	W >85 ± 5, Co <80 ± 5	WO_3 >99 ± 0.5	Suitable for complex waste (additives <5%±0.5%), TiC residue <0.05%±0.01%, and low Co recovery rate needs to be optimized.
Mechanical crushing and sorting	>80 ± 5	>98 ± 0.5	Suitable for simple waste (additives <2%±0.5%), impurities (Fe, Si) <0.05%±0.01%, slightly lower purity.
Arc melting method	>80 ± 5	>98 ± 0.5	Suitable for high hardness scrap (HV>1800±30), oxygen content <0.01%±0.001%, and low recovery rate limiting applications.
Electrolytic dissolution	Co >90 ± 5, WC >85 ± 5	>99 ± 0.5	Suitable for medium and low Co waste (Co 6-10%±1%), impurities <0.01%±0.001%, high efficiency and high purity.
Electrochemical oxidation method	W >85 ± 5, Co <80 ± 5	WO_3 >99 ± 0.5	Suitable for complex waste (TiC/VC<5%±0.5%), C residue<0.05%±0.01%, Co recovery rate needs to be improved.
High-temperature chlorination	W >90 ± 5, Co <75 ± 5	WO_3 >99 ± 0.5	Suitable for high tungsten scrap (WC>90%±1%), Cl residual <0.01%±0.001%, and low Co recovery rate.
Vacuum evaporation method	Co >85 ± 5, WC >80 ± 5	>98 ± 0.5	Suitable for high Co scrap (Co>10%±1%), O content <0.01%±0.001%, slightly lower purity requires refining.

16.1.6 Comprehensive Comparison of Cemented Carbide Recycling Technologies

Cemented carbide recovery technologies utilize a variety of methods to recycle tungsten (WC >85% ± 1%) and cobalt (Co 6%-15% ± 1%), including chemical methods (such as zinc smelting, acid leaching, oxidation roasting and alkaline leaching), physical methods (such as mechanical crushing and sorting, arc melting), electrochemical methods (such as electrolytic dissolution and electrochemical oxidation), and thermal treatment and volatilization methods (such as high-temperature chlorination and vacuum volatilization). These technologies exhibit significant differences in recovery rates (70%-95% ± 5%), product purity (95%-99.5% ± 0.5%), and applicable waste types. The selection of a recovery technology requires a comprehensive consideration of waste characteristics, process efficiency, and resource utilization. This section provides a detailed comparison of recovery rates and purity, as well as applicable waste types, and offers optimization recommendations based on industry trends.

16.1.6.1 Cemented Carbide Recovery Rate and Purity

Comparative Overview of Cemented Carbide Recycling Technologies:
Recovery rate and purity are key indicators for evaluating recycling technology efficiency and product quality. Recovery rate reflects the proportion of tungsten and cobalt extracted from scrap (target >85% ± 5%), directly impacting resource utilization efficiency. Purity determines the reusability of recycled materials (target >98% ± 0.5%) and is particularly crucial in high-end applications such as aerospace tools and battery materials. Testing methods include chemical analysis (recovery, precision ±1%, RSD <5%, sample size 1 g ± 0.01 g), ICP-MS (purity, detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm), XRD (phase composition, scan range 10°-90°, step size 0.02° ± 0.01°, precision ±1%), and SEM (morphology, resolution <0.1 µm ± 0.01 µm, magnification 5000-10,000x). In addition, particle size distribution (laser particle size analysis, measuring range 0.01-1000 µm ± 0.05 µm) and surface roughness (Ra <0.1 µm ± 0.01 µm) are also used to evaluate product quality consistency.

Comparison of cemented carbide recycling technologies

The zinc smelting method achieves
WC and Co recovery rates >90% ± 5% and purity >99% ± 0.5%. Efficient separation is achieved through a zinc smelting process at 800-1000°C ± 10°C, making it suitable for high-Co scrap (Co >10% ± 1%). Residual Zn is <0.01% ± 0.001% (EDS verified, detection limit 0.001% ± 0.0001%), with uniform particle size (1-5 µm ± 0.1 µm, D90/D10 <5), and morphological roundness >90% ± 2%.

Acid leaching achieves
Co recovery rates >95% ± 2%, WC recovery rates >85% ± 5%, and purity >99% ± 0.5%. Selective leaching using H_2SO_4 or HCl (concentration 1-2 mol/L ± 0.1 mol/L, temperature 40-60°C ± 5°C, soak time 1-2 h ± 0.1 h) results in WC dissolution rates <0.1% ± 0.01% (XRD analysis: impurities

<0.05% ± 0.01%). Fe/Ni impurities <0.01% ± 0.001% (ICP-MS). Suitable for medium- and low-cobalt waste (Co 6%-10% ± 1%), particle size 1-3 μm ± 0.1 μm.

The oxidation roasting and alkaline leaching method

achieves tungsten recovery rates >85% ± 5%, Co recovery rates <80% ± 5%, and WO_3 purity >99% ± 0.5%. After oxidation at 600-800°C ± 10°C, leaching is performed using a NaOH solution (concentration 2-4 mol/L ± 0.1 mol/L, temperature 80-100°C ± 5°C, time 2-3 h ± 0.1 h). This method is suitable for complex waste materials (TiC/VC additives <5% ± 0.5%). TiC residue is <0.05% ± 0.01% (SEM observation), particle morphology retention is >90% ± 2%, and particle size is 1-5 μm ± 0.1 μm.

Mechanical crushing and separation achieves

a recovery rate >80% ± 5% and a purity >98% ± 0.5%. Using a jaw crusher (particle size 1-10 mm ± 0.1 mm, efficiency >95% ± 2%) and magnetic separation (magnetic field strength 0.5-1 T ± 0.1 T), this process is suitable for simple waste materials (additives <2% ± 0.5%). Impurities (Fe, Si) are <0.05% ± 0.01% (EDS analysis), particle size distribution uniformity is <5% ± 1%, and surface roughness Ra is <0.1 μm ± 0.01 μm.

Arc melting offers

a recovery rate of >80% ± 5% and a purity of >98% ± 0.5%. Arc melting is suitable for melting high-hardness scrap (HV >1800 ± 30) at 2000-2500°C ± 50°C (current 500-1000 A ± 50 A, voltage 20-40 V ± 2 V), with an oxygen content of <0.01% ± 0.001% (TGA measurement, weight loss <0.1% ± 0.01%). This method is also suitable for high-density scrap (density >14 g/cm³). ± 0.1 g/cm³) . Particle uniformity >95% ± 2%, particle size 1-5 μm ± 0.1 μm.

Electrolytic dissolution method

Co recovery rate>90% ± 5%, WC recovery rate>85% ± 5%, purity>99% ± 0.5%. At 50-200 A/ m² Operating at a current density of ± 10 A/ m² and an electrolyte (H_2SO_4 1-2 mol/L ± 0.1 mol/L) at 20-40°C ± 5°C, the system is suitable for low- to medium-cobalt waste (Co 6%-10% ± 1%). Impurities are <0.01% ± 0.001% (ICP-MS), conductivity is $>10^4$S / m ± 10^3S /m, and particle size is 1-3 μm ± 0.1 μm.

Electrochemical oxidation method

tungsten recovery rate>85% ± 5%, Co recovery rate<80% ± 5%, WO_3 purity >99% ± 0.5%. At 50-100 A/ m² Electrolytic treatment at a current density of ± 5 A/ m² and a temperature of 60-80°C ± 5°C is suitable for complex waste materials (TiC/VC <5% ± 0.5%). Residual carbon is <0.05% ± 0.01% (XRD analysis), the morphology is porous (pore size <1 μm ± 0.1 μm), and the particle size is 1-5 μm ± 0.1 μm.

The high-temperature chloride process

achieves tungsten recovery rates >90% ± 5%, Co recovery <75% ± 5%, and WO_3 purity >99% ± 0.5%. Operating at 800-1000°C ± 10°C and a Cl_2 flow rate of 10-30 L/min ± 1 L/min, it is suitable

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for high-tungsten scrap (WC >90% ± 1%). Residual Cl_2 is <0.01% ± 0.001% (verified by EDS), particle size is 1-5 μm ± 0.1 μm, and morphology circularity is >90% ± 2%.

Vacuum **volatilization achieves**
Co recovery rates >85% ± 5%, WC recovery rates >80% ± 5%, and purity >98% ± 0.5%. Volatilization is performed at 1000-1200°C ± 10°C and a vacuum pressure <10^{-2} Pa ± 10^{-3} Pa , making it suitable for high-Co scrap (Co >10% ± 1%). Oxygen content is <0.01% ± 0.001% (EDS), particle uniformity >95% ± 2%, and particle size 1-3 μm ± 0.1 μm.

Analysis and summary of cemented carbide recycling technology

leaching
(Co >95% ± 2%) and zinc smelting (WC/Co >90% ± 5%) offer the highest recovery rates, making them suitable for efficient resource utilization. Mechanical crushing and sorting and arc melting have the lowest recovery rates (<85% ± 5%), limited by the complexity of the waste materials. Electrolytic dissolution and high-temperature chlorination offer a balanced performance between medium and high recovery rates (>90% ± 5%), making them suitable for diverse needs.

smelting
, acid leaching, electrolytic dissolution, and high-temperature chlorination methods offer the highest purity (>99% ± 0.5%), meeting the needs of high-end applications. Mechanical crushing and sorting and arc melting methods offer slightly lower purity (>98% ± 0.5%), but the processes are simpler. Vacuum volatilization and oxidative roasting and alkaline leaching methods offer stable purity (>98% ± 0.5%), but are affected by process conditions and waste composition.

Influencing factors:
Scrap composition (Co content 6%-15% ± 1%, additives TiC/VC <5% ± 0.5%) significantly affects the recovery rate. High-Co scrap is more suitable for zinc melting and vacuum volatilization. Acid leaching and electrolytic dissolution are preferred for medium- and low-Co scrap. Process parameters such as current density (50-200 A/m²) are also important. Purity is directly determined by the following factors: magnetic field (magnetic field) (± 10 A/m²) , reaction temperature (800-1200°C ± 10°C), and separation accuracy (magnetic field 0.5-1 T ± 0.1 T). Waste particle size (1-10 mm ± 0.1 mm) and pretreatment quality (e.g., oil removal <0.1% ± 0.01%) are also crucial.

Optimization Recommendations:
For high-Co scrap, zinc smelting (comprehensive recovery >90% ± 5%) or vacuum volatilization (Co >85% ± 5%) are preferred. For medium- and low-Co scrap, acid leaching (Co >95% ± 2%) or electrolytic dissolution (Co >90% ± 5%) are recommended. Complex scrap (such as those containing TiC/VC) can be treated with electrochemical oxidation or oxidation roasting and alkaline leaching. Simple scrap is suitable for mechanical crushing and sorting (purity >98% ± 0.5%). Pre-treatment of the scrap using a combination of XRF analysis (accuracy ±0.1%) and ultrasonic cleaning (residue <0.1% ± 0.01%) can improve recovery and purity consistency.

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16.1.6.2 Analysis and Summary

are

specifically designed for high-Co scrap (adaptability >85% ± 2%). Acid leaching and electrolytic dissolution are superior for medium- and low-Co scrap (adaptability >90% ± 2%). Oxidation roasting, alkaline leaching, and electrochemical oxidation are suitable for complex scrap (adaptability >85% ± 2%). Mechanical sorting is suitable for simple scrap (adaptability >90% ± 2%). Arc melting is suitable for high-hardness scrap, but its adaptability is slightly lower (>80% ± 2%).

Influencing factors:

Scrap composition (Co content, additive type and content), particle size (1-10 mm ± 0.1 mm), and pretreatment quality (e.g., oil removal <0.1% ± 0.01%) directly influence suitability. High-Co scrap requires high-temperature processing, complex scrap requires multi-step treatment, and simple scrap relies more on physical methods.

Optimization recommendations

include using XRF pre-analysis (accuracy ±0.1%) and SEM morphology assessment (resolution <0.1 μm ± 0.01 μm) to classify waste materials and match them to the optimal technology. For example, zinc smelting or vacuum volatilization is recommended for high-Co scrap, acid leaching or electrolytic dissolution is recommended for medium- and low-Co scrap, oxidation roasting, alkaline leaching, or electrochemical oxidation is recommended for complex scrap, and mechanical sorting is preferred for simple scrap. Optimizing pretreatment (such as ultrasonic cleaning with a residue of <0.1% ± 0.01%) can improve adaptability by >90% ± 2%.

Comparison table of energy consumption and cost of cemented carbide recycling technology

technology	Energy consumption (kWh/t)	Cost (relative to raw extraction)	Features and Remarks
Zinc melting method	>800 ± 50 (vacuum furnace 900-1000°C±10°C)	Higher (equipment investment and Zn volatilization, about 40-50%±5%)	High recovery rate (W: 90-96%), Zn recycling rate> 95%, suitable for WC-Co waste, with excellent overall cost performance.
Acid leaching	<500 ± 50 (normal pressure 60-80°C±5°C)	Low (waste liquid treatment increased by 10%±2%, about 20-30%±5%)	Low energy consumption, waste liquid circulation rate>90%, suitable for high purity requirements, waste liquid treatment costs need to be optimized.
Oxidation roasting alkaline leaching	>1000 ± 100 (calcined at 800-1000°C±10°C)	Medium (multi-step process, about 30-40% ± 5%)	Suitable for complex waste (W-Ni-Fe), reduces pretreatment costs, and high energy consumption needs to be improved.
Mechanical crushing and sorting	<400 ± 50 (crushing 50-100 MPa±1 MPa)	Lowest (<30%±5%)	Minimum energy consumption, low equipment investment, low purity (90-95%), and requires

			subsequent refining.
Arc melting method	>1000 ± 100 (>3000°C±100°C)	High (arc furnace investment and maintenance, >50%±5%)	Suitable for high hardness scrap, large batch (10-100 t/batch), and high energy consumption restrictions.
Electrolytic dissolution	<600 ± 50 (50-150 A/m² ± 10 A/ m²)	Moderate (electrode loss 5% ± 1%, about 30-40% ± 5%)	The waste liquid recycling rate is >90%, which is suitable for WC-Co waste and has high cost performance. However, electrode loss needs to be paid attention to.
Electrochemical oxidation method	>700 ± 50 (100-200 A/m² ± 10 A/ m²)	Medium (multi-step purification, about 35-45% ± 5%)	Suitable for complex waste materials, reduces pretreatment costs, and the complex process limits scalability.
High-temperature chlorination	>800 ± 50 (800-1000°C±10°C)	Higher (Cl_2 corrodes equipment, maintenance 10%±2%, about 40-50%±5%)	High tungsten recovery rate (W: 95-99%), equipment corrosion increases maintenance costs.
Vacuum evaporation method	>900 ± 50 (1000-1200°C±10°C, <10^{-2} Pa ± 10^{-3} Pa)	High (vacuum equipment investment, >40%±5%)	Suitable for high-Co waste, high purity (>99%), high equipment investment limits popularization.

16.1.6.3 Environmental Impact of Cemented Carbide Recycling Technology

Comparative Overview of Cemented Carbide Recycling Technologies

Environmental impact is the core indicator for evaluating the sustainability of recycling technologies, covering greenhouse gas emissions (such as CO_2 emissions , target <1.5 t CO_2 / t ± 0.2 t CO_2 / t), waste liquid/waste gas emissions (target <1% ± 0.1%), and waste reduction efficiency (target >40% ± 5%). Testing methods include life cycle assessment (LCA, accuracy of ±0.1 t CO_2 / t, based on ISO 14040, covering the entire supply chain from raw material extraction to waste treatment), wastewater analysis (accuracy of ±0.1%, using ICP-MS and infrared spectroscopy, detection limit of 0.001% ± 0.0001%), waste gas concentration measurement (accuracy of ±5 mg/m³ , using FT-IR spectroscopy, range of 0-500 mg/m³) , and mass balance analysis (accuracy of ±1 kg/t, RSD <5%, sample size of 1 t ± 0.01 t). Resource consumption (e.g., water usage 5-20 m³ / t ± 1 m³ / t) and energy mix (renewable energy share >20% ± 5%) are also assessed.

Comparison of cemented carbide recycling technologies

Zinc smelting produces

CO_2 emissions of 1.5 t CO_2 / t ± 0.2 t CO_2 / t, primarily due to the energy-intensive high-temperature smelting process (800-1000°C ± 10°C). Wastewater emissions are <0.2% ± 0.05% (Zn residue after distillation, EDS determination of Zn content <0.01% ± 0.001%), controlled by a highly efficient condensation system (recovery rate >95% ± 1%). Waste reduction is >40% ± 5% (mass balance verification, residual <5% ± 1%), with no chemical waste generated and waste gas CO concentration

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<50 mg/m³ . ± 5 mg/ m³ (multi-stage filtration efficiency >98% ± 1%).

Acid leaching produces

CO_2 emissions of 1 t CO_2 / t ± 0.1 t CO_2 / t, benefiting from low energy consumption (<600 kWh/t ± 50 kWh/t) and the partial use of renewable energy. Wastewater emissions are 0.5%-1% ± 0.1% (after neutralization with HNO_3 or HCl, pH 6-8 ± 0.1, COD <100 mg/L ± 10 mg/L). A recycling system (recovery rate >90% ± 5%) significantly reduces environmental impact. Waste reduction is >40% ± 5% (residual WC recycling rate >85% ± 2%), and waste gas NO_x concentration is <100 mg/m³ . ± 5 mg/ m³ (SCR denitrification efficiency>90% ± 2%).

CO_2 emissions from **the oxidation roasting and alkaline leaching process** are 2 t CO_2 / t ± 0.2 t CO_2 / t, resulting from high-temperature roasting (600-800°C ± 10°C) and oxidation reactions (O_2 consumption 0.1-0.2 kg/t ± 0.01 kg/t). Wastewater emissions are <0.5% ± 0.1% (after neutralization with NaOH solution, pH 7-9 ± 0.1, Na^+ concentration <500 mg/L ± 50 mg/L, recycling rate >85% ± 2%). Waste gas CO_2 capture efficiency is >80% ± 5% (amine absorption method, efficiency >85% ± 2%), waste reduction is >40% ± 5% (WO_3 recovery rate >85% ± 2%), and waste gas SO_2 concentration is <150 mg/ m³. ± 5 mg/ m³ .

Mechanical crushing and sorting

emits 0.8 t CO_2 /t ± 0.1 t CO_2 / t of CO_2 . This technology is energy-efficient (<400 kWh/t ± 50 kWh/t), primarily using electricity (>30% ± 5% renewable energy). There is no significant liquid waste (<0.1% ± 0.01%, oil residue <0.05% ± 0.01% via infrared detection), and waste reduction is >40% ± 5% (magnetic separation recovery rate >90% ± 2%). Exhaust gas dust concentration is <50 mg/m³ . ± 5 mg/m³ (bag filter efficiency >99% ± 1%), noise level <85 dB ± 5 dB.

Arc melting

CO_2 emissions are 1.2 t CO_2 / t ± 0.2 t CO_2 / t, due to high energy consumption (2000-2500°C ± 50°C , 500-1000 A ± 50 A). Waste emissions are <0.1% ± 0.01% (under argon protection, slag residue is <0.05% ± 0.01%), and waste reduction is >35% ± 5% (slag recycling rate is >80% ± 2%). Exhaust gas CO and NOx concentrations are <200 mg/m³ . ± 5 mg/ m³ (multi-stage catalytic purification efficiency> 95% ± 1%), thermal radiation needs to be shielded (<100 W/ m² ± 10 W/m²) .

Electrolytic dissolution

CO_2 emissions are 1 t CO_2 / t ± 0.1 t CO_2 / t , primarily driven by electricity consumption (600-800 kWh/t ± 50 kWh/t). Wastewater emissions are <0.5% ± 0.1% (H_2SO_4 electrolyte , recycling rate > 90% ± 5%, pH adjusted to 6-8 ± 0.1), and waste reduction is >40% ± 5% (Co recovery rate >90% ± 2%). Exhaust gas H_2 concentration is <50 mg/ m³. ± 5 mg/ m³ (safety discharge, detection limit 10 mg/m³) ± 1 mg/m³) , water consumption 10-15 m³ / t ± 1 m³ / t.

Electrochemical oxidation

CO_2 emissions: 1.1 t CO_2 / t ± 0.1 t CO_2 / t, electrolysis process (50-100 A / m² ± 5 A/m²) . Wastewater discharge <0.5% ± 0.1% (NaOH circulation, pH 7-9 ± 0.1, COD <150 mg/L ± 10 mg/L, recovery rate >85% ± 2%), waste reduction >35% ± 5% (WO_3 recovery rate >85% ± 2%). Waste gas O_2 concentration <100 mg/ m³ ± 5 mg/m³ (emission control efficiency >90% ± 2%), electrode loss <5% ± 1%.

High-temperature chlorination

CO_2 emissions are 1.5 t CO_2 / t ± 0.2 t CO_2 / t, caused by the Cl_2 reaction (800-1000°C ± 10°C) and high-temperature process. Waste gas HCl capture efficiency is >95% ± 2% (NaOH absorption, residual <5 mg/m³). ± 1 mg/m³) , waste liquid discharge <0.2% ± 0.05% (Cl^- concentration <200 mg/L ± 20 mg/L). Waste material reduction >40% ± 5% (WC recovery rate >90% ± 2%), exhaust gas Cl_2 concentration <50 mg/ m³ ± 5 mg/ m³ .

Vacuum volatilization produces

CO_2 emissions of 0.9 t CO_2 / t ± 0.1 t CO_2 / t. Vacuum conditions (<10^{-2}Pa ± 10^{-3}Pa) reduce energy consumption. There is no significant liquid waste (<0.1% ± 0.01%, oil contamination <0.05% ± 0.01%), and waste reduction is >40% ± 5% (Co recovery rate >85% ± 2 %). Waste gas emissions are <50 mg/m³ . ± 5 mg/ m³ (HEPA filtration efficiency >99% ± 1%), vacuum pump leakage rate <0.01% ± 0.001%.

Analysis and summary of cemented carbide recycling technology

crushing

and sorting (0.8 t CO_2 / t ± 0.1 t CO_2 / t) and vacuum volatilization (0.9 t CO_2 / t ± 0.1 t CO_2 / t) have the lowest **CO_2** emissions, demonstrating their low energy consumption. Oxidation roasting and alkaline leaching (2 t CO_2 / t ± 0.2 t CO_2 / t) has the highest CO_2 emissions, requiring optimization of roasting efficiency. Zinc melting (1.5 t CO_2 / t ± 0.2 t CO_2 / t) and high-temperature chlorination (1.5 t CO_2 / t ± 0.2 t CO_2 / t) have medium-to-high emissions, while arc melting (1.2 t CO_2 / t ± 0.2 t CO_2 / t) has a moderate emission rate.

Waste liquid/waste gas emission

mechanical sorting, vacuum volatilization and arc melting methods have no significant waste liquid (<0.1% ± 0.01%), and waste gas is well controlled (<50-200 mg/ m³ ± 5 mg/m³) ; acid leaching (0.5%-1% ± 0.1%) and electrochemical oxidation (<0.5% ± 0.1%) require enhanced wastewater recycling (target >95% ± 2%). The HCl capture rate for high-temperature chlorination waste gas is >95% ± 2%, and the CO_2 capture rate for oxidation roasting and alkaline leaching is >80% ± 5%, requiring further improvement.

The waste reduction methods

of zinc smelting, acid leaching, electrolytic dissolution, high-temperature chlorination and vacuum volatilization are >40% ± 5%, while the mechanical sorting and electrochemical oxidation methods are slightly lower (>35% ± 5%), reflecting the efficient utilization of resources.

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The main variables are

energy consumption (<600 kWh/t ± 50 kWh/t for significant CO_2 reductions) , wastewater recycling rate (>90% ± 5% for emissions reductions), waste gas capture efficiency (>80% ± 5% for pollution control), and energy mix (renewable energy share >20% ± 5%). Waste pretreatment (e.g., oil removal <0.1% ± 0.01%) and equipment maintenance (e.g., vacuum tightness >99% ± 0.5%) also influence the environmental footprint.

Optimization recommendations

prioritize mechanical separation (CO_2 0.8 t CO_2 / t ± 0.1 t CO_2 / t) or vacuum volatilization (CO_2 0.9 t CO_2/t ± 0.1 t CO_2/t) to achieve low emissions. Acid leaching and electrolytic dissolution methods can reduce wastewater impacts by optimizing wastewater recycling systems (increasing recovery rates to >95% ± 2%) and introducing membrane separation technology (reducing COD by > 20% ± 2%). For oxidative roasting and alkaline leaching, high-efficiency CO_2 capture technology (such as molecular sieve adsorption, with efficiencies >90% ± 2%) and low-temperature roasting (<600°C ± 10°C) are recommended to achieve emission reductions of >15% ± 2%. High-temperature chlorination requires enhanced HCl capture facilities (residues <1 mg/m³). ± 0.1 mg/m³) and optimized Cl_2 recovery rates (>98% ± 1%). Promote renewable energy (>30% ± 5%) and exhaust gas purification systems (multi-stage filtration, efficiency >99% ± 1%) to ensure an overall environmental impact of less than 1 t CO_2 / t ± 0.2 t CO_2 / t, in line with 2025 environmental standards.

Comparison table of environmental impact of cemented carbide recycling technologies

technology	CO_2 emissions t CO_2 / t	Waste liquid/waste gas emissions (%)	scrap Reduction%	Features and Remarks
Zinc melting method	1.5 ± 0.2	Waste liquid <0.2 ± 0.05 (Zn distillation)	>40 ± 5	High energy consumption (900-1000°C), no chemical waste, Zn recycling rate >95%, suitable for WC-Co waste.
Acid leaching	1.0 ± 0.1	Wastewater 0.5-1.0 ± 0.1 (neutralized by HNO_3)	>40 ± 5	Low energy consumption, waste liquid circulation rate>90%, suitable for high purity requirements, and high waste liquid treatment costs.
Oxidation roasting alkaline leaching	2.0 ± 0.2	Waste liquid <0.5 ± 0.1 (NaOH circulation), waste gas CO_2 capture rate >80% ± 5%	>40 ± 5	Roasting (800-1000°C) produces high CO_2 emissions , and NaOH circulation reduces waste liquid, requiring waste gas capture.
Mechanical crushing and sorting	0.8 ± 0.1	No waste liquid (<0.1 ± 0.01)	>40 ± 5	Minimum energy consumption, no chemical waste, low purity (90-95%), and requires subsequent refining.
Arc melting method	1.2 ± 0.2	Waste liquid <0.1 ± 0.01 (argon protection)	>35 ± 5	High energy consumption (1500-2000°C), argon protection reduces waste liquid, and the waste

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				reduction is slightly lower.
Electrolytic dissolution	1.0 ± 0.1	Waste liquid <0.5 ± 0.1 (H_2SO_4 circulation rate >90% ± 5 %)	>40 ± 5	The power consumption is moderate, the waste liquid circulation rate is high, suitable for WC-Co waste, and the electrode loss needs to be optimized.
Electrochemical oxidation method	1.1 ± 0.1	Waste liquid <0.5 ± 0.1 (NaOH circulation)	>35 ± 5	The power consumption is moderate, waste liquid circulation reduces emissions, waste material reduction is slightly lower, and the process is complex.
High-temperature chlorination	1.5 ± 0.2	Waste liquid <0.2 ± 0.05, waste gas HCl capture rate >95% ± 2%	>40 ± 5	The Cl_2 reaction produces high CO_2 emissions , high HCl capture efficiency, and less waste liquid, but equipment corrosion requires attention.
Vacuum evaporation method	0.9 ± 0.1	No waste liquid (<0.1 ± 0.01)	>40 ± 5	Vacuum has low energy consumption, no chemical waste liquid, high equipment investment, and is suitable for small batches of high purity.

16.1.6.4 Types of Waste Applicable to Cemented Carbide Recycling Technology

Comparative Overview:

The diversity of scrap types forms the basis for evaluating the suitability of cemented carbide recycling technologies, directly influencing process selection and recycling efficiency. Scrap types primarily include high-Co scrap (Co >10% ± 1%), low-Co scrap (Co <10% ± 1%), high-hardness scrap (HV >1800 ± 30), and complex scrap (TiC/VC additives <5% ± 0.5%). These scraps come from a wide range of sources. For example, high-Co scrap is often found in discarded high-performance tools and wear-resistant coatings, while low-Co scrap is often found in worn molds and high-precision components. High-hardness scrap primarily originates from super-hard carbide coatings, while complex scrap includes multi-phase mixed waste, such as TiC/VC coating fragments. The suitability assessment is based on several key indicators: recovery rate (target >80% ± 5%, reflecting the extraction efficiency of tungsten and cobalt, which is directly related to resource utilization), purity (target >98% ± 0.5%, which determines the reuse value of the recovered material and is particularly important in the aerospace and electronics industries) and process stability (batch deviation <1% ± 0.2%, ensuring production consistency and reducing quality fluctuations). Testing methods include XRF analysis (waste composition, accuracy ±0.1%, detection limit 0.01% ± 0.001%, covering Ti-Zn elements, scanning time 100-200 s ± 10 s), recovery efficiency assessment (mass balance method, accuracy ±1%, RSD <5%, sample size 1 t ± 0.01 t, average value of multiple measurements), SEM morphology observation (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x, observation field 10-20) and XRD phase composition analysis (scanning range 10°-90°, step size 0.02° ± 0.01°, accuracy ±1%, 2θ angle correction ±0.02°). In addition, particle size distribution (laser particle size analysis, range 0.01-1000 μm ± 0.05 μm, repeated 3-5 times) and surface roughness (Ra <0.1 μm ± 0.01 μm, contact probe measurement, sampling points >1000 points) further assist in waste classification and process matching. Refer to industry data (such as the China Tungsten Online Scrap Classification Standards and Recycling Technology Trend Report)

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on July 20, 2025, 14:44 HKT) and combine the physical and chemical properties of the waste (such as density 14-15 g/cm³). ± 0.1 g/cm³ , hardness HV 1600-2000 ± 30) and pre-treatment status (e.g. oil residue <0.1% ± 0.01%). This section systematically compares the optimal recycling technology for different waste types and provides detailed optimization solutions.

Technology Comparison

The zinc melting method

is suitable for high-Co scrap (Co >10% ± 1%, such as WC-12Co, WC-15Co, density >14 g/cm³) ± 0.1 g/cm³) , typical sources include scrapped high-speed steel tools and wear-resistant coating fragments containing high amounts of Co. Recovery is >90% ± 5% (combined extraction of Co and WC, verified by mass balance, RSD <3%), purity is >99% ± 0.5% (ICP-MS analysis, impurities Fe/Ni <0.01% ± 0.001%, detection limit 0.0001% ± 0.00001%), and process stability is high (batch variation <0.5% ± 0.1%, based on data from 10 batches, SEM morphology consistency >95% ± 2%). Uniform particles (1-5 µm ± 0.1 µm, D90/D10 <5, verified by laser particle size analysis) and morphological roundness >90% ± 2% (SEM observation) are required. Suitable for scrap with high and uniform Co content, with limited additive interference (TiC/VC <1% ± 0.1%) and limited influence (XRD impurities <0.05% ± 0.01%). High-temperature melting (800-1000°C ± 10°C) is required for efficient Zn recovery (>95% ± 1%), and high scrap particle size (1-10 mm ± 0.1 mm) is required.

The acid leaching method

is suitable for low-Co scrap (Co 6%-10% ± 1%, such as WC-6Co and WC-8Co), commonly found in worn molds, low-Co alloy scrap, and some scrapped tool heads. Co recovery rates are >95% ± 2% (H_2SO_4 1-2 mol /L ± 0.1 mol/L, 40-60°C ± 5°C, immersion time 1-2 h ± 0.1 h , reaction rate 0.5-1 g/min ± 0.1 g/min). WC recovery rates are >85% ± 5% (dissolution rate <0.1% ± 0.01%, verified by XRD, impurities <0.05% ± 0.01%), and purity is >99% ± 0.5% (impurities <0.01% ± 0.001%, verified by ICP-MS). The process offers excellent stability (batch variation <0.5% ± 0.1%, based on data from 15 batches), making it particularly suitable for simple scrap materials (additive content <2% ± 0.5%, e.g., without TiC/VC, verified by XRF). Particle size is 1-3 µm ± 0.1 µm (laser particle size analysis, distribution width <10% ± 1%), and morphological roundness >90% ± 2% (SEM). High scrap pretreatment requirements are met (oil contamination <0.05% ± 0.01%, ultrasonic cleaning efficiency >95% ± 2%). Particle size control (1-5 mm ± 0.1 mm) enhances selectivity.

The oxidation roasting and alkaline leaching method

is suitable for complex scrap (TiC/VC additives <5% ± 0.5%, such as WC-10Co-TiC and WC-8Co-VC), commonly found in multiphase coating scrap and mixed alloy fragments. Tungsten recovery rates are >85% ± 5% (oxidation at 600-800°C ± 10°C, O_2 consumption 0.1-0.2 kg/t ± 0.01 kg/t, NaOH 2-4 mol/L ± 0.1 mol/L leaching, 2-3 h ± 0.1 h). WO_3 purity is >99% ± 0.5% (residual TiC impurity <0.05% ± 0.01%, XRD detection, detection limit 0.001% ± 0.0001%). Co recovery rates are <80% ± 5% (low selectivity, due to some Co oxidation loss). The process offers moderate

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process stability (batch variation <1% ± 0.2% based on 10 batches), low additive interference (compatibility >85% ± 2%, SEM morphology variation <0.1% ± 0.02%), and particle size of 1-5 μm ± 0.1 μm (distribution uniformity <5% ± 1%). Suitable for multi-component scrap (TiC/VC ratio 1%-5% ± 0.1%), the oxidation temperature must be optimized (<700°C ± 10°C) to minimize Co loss.

Mechanical crushing and sorting

is suitable for simple scrap (additives <2% ± 0.5%, such as WC-10Co and WC-8Co), primarily single-component scrap (such as scrapped cutter heads and worn parts). Recovery rates are >80% ± 5% (jaw crusher particle size 1-10 mm ± 0.1 mm, efficiency >95% ± 2%, magnetic separation field strength 0.5-1 T ± 0.1 T), and purity >98% ± 0.5% (Fe/Si impurities <0.05% ± 0.01%, EDS verification, detection limit 0.001% ± 0.0001%). However, for scrap with high additive content (TiC/VC >2% ± 0.5%), purity drops to <98% ± 0.5% (XRD impurities >0.1% ± 0.02%). High process stability (batch deviation <0.5% ± 0.1%, based on 20 batches), particle distribution uniformity <5% ± 1% (laser particle size analysis), particle size 1-10 μm ± 0.1 μm, surface roughness Ra <0.1 μm ± 0.01 μm (touch probe). Suitable for low-complexity waste materials that require dust control (<10 mg/m^3). ± 1 mg/m^3 , bag filter efficiency >99% ± 1%).

Arc melting

is suitable for high-hardness scrap (HV >1800 ± 30, such as WC-12Co and WC-15Co), commonly found in wear-resistant parts, superhard coatings, and high-temperature alloy scrap. Recovery rates are >80% ± 5% (2000-2500°C ± 50°C, current 500-1000 A ± 50 A, voltage 20-40 V ± 2 V), purity >98% ± 0.5% (oxygen content <0.01% ± 0.001%, TGA weight loss <0.1% ± 0.01%), and delamination >90% ± 2% (phase separation efficiency verified by SEM, 10-20 field of view). Moderate process stability (batch variation <1% ± 0.2%, based on 10 batches), particle uniformity >95% ± 2% (laser particle size analysis), particle size 1-5 μm ± 0.1 μm, suitable for high density (>14 g/cm^3) ± 0.1 g/cm^3) and high hardness scrap (HV 1800-2000 ± 30). Sensitive to additives (TiC/VC >1% ± 0.1% affects delamination, XRD impurity >0.05% ± 0.01%), requiring pre-sorting.

Electrolytic dissolution

is suitable for medium and low Co scrap (Co 6%-10% ± 1%, such as WC-8Co, WC-6Co), including worn tools, low Co alloys and some coating scraps. Co recovery rate >90% ± 5% (50-200 A/m^2) ± 10 A/m^2 , 20-40°C ± 5°C, H_2SO_4 1-2 mol /L ± 0.1 mol/L, current efficiency >85% ± 2 %), WC recovery >85% ± 5%, purity >99% ± 0.5% (impurities <0.01% ± 0.001%, ICP-MS, detection limit 0.0001% ± 0.00001%). High process stability (batch variation <0.5% ± 0.1% based on 15 batches), particle size 1-3 μm ± 0.1 μm (laser particle size analysis, distribution width <10% ± 1%), conductivity >10^4 S /m ± 10^3 S/m (influenced by electrolyte purity). Suitable for homogeneous waste materials, requiring controlled electrode loss (<5% ± 1%) and waste liquid circulation (>90% ± 2%).

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Electrochemical oxidation
is suitable for complex scrap (TiC/VC additives <5% ± 0.5%, such as WC-10Co-VC, WC-8Co-TiC), which is commonly found in multi-phase coating scrap and mixed alloy fragments. Tungsten recovery rate >85% ± 5% (50-100 A/m²) ± 5 A/m² , 60-80°C ± 5°C, electrolysis efficiency >80% ± 2%), WO_3 purity >99% ± 0.5% (residual C <0.05% ± 0.01%, XRD, detection limit 0.001% ± 0.0001%), Co recovery <80% ± 5% (partial Co loss due to oxidation). Process stability is moderate (batch variation <1% ± 0.2%, based on 10 batches), additive compatibility is good (interference <0.05% ± 0.01%, SEM morphology variation <0.1% ± 0.02%), and particle size is 1-5 μm ± 0.1 μm (distribution uniformity <5% ± 1%). Suitable for multi-component scrap (TiC/VC 1%-5% ± 0.1%), requiring optimized electrode life (>500 h ± 50 h) and current density (<100 A/m²) ± 5 A/m²) .

The high-temperature chloride method
is suitable for high-tungsten scrap (WC >90% ± 1%, such as WC-6Co and WC-4Co), including high-tungsten-content cutting tools, abrasives, and coating scrap. Tungsten recovery rates are >90% ± 5% (800-1000°C ± 10°C, Cl_2 flow rate 10-30 L/min ± 1 L/min, reaction rate 0.5-1 g/min ± 0.1 g/min), WO_3 purity >99% ± 0.5% (TiC residue <0.05% ± 0.01%, EDS, detection limit 0.001% ± 0.0001%), and Co recovery <75% ± 5% (low selectivity). High process stability (batch variation <0.5% ± 0.1%, based on 15 batches), particle size 1-5 μm ± 0.1 μm (laser particle size analysis, distribution width <10% ± 1%), and morphology circularity >90% ± 2% (SEM). Suitable for scrap with a high WC content (>90% ± 1%, verified by XRF), with controlled Cl_2 residual (<0.01% ± 0.001%).

The vacuum volatilization method
is suitable for high-Co scrap (Co >10% ± 1%, such as WC-12Co and WC-15Co), including high-Co coating scrap and scrapped tools. Co recovery rates are >85% ± 5% (1000-1200°C ± 10°C, vacuum <10^{-2} Pa ± 10^{-3} Pa , volatilization efficiency >90% ± 2%), WC recovery rates are > 80% ± 5%, and purity is >98% ± 0.5% (O content <0.01% ± 0.001%, EDS, detection limit 0.0001% ± 0.00001%). High process stability (batch variation <0.5% ± 0.1% based on 10 batches), excellent performance for simple scrap (additive content <1% ± 0.1%, XRD impurity content <0.05% ± 0.01%), particle uniformity >95% ± 2% (laser particle size analysis), particle size 1-3 μm ± 0.1 μm (distribution width <5% ± 1%). Suitable for high-Co scrap, vacuum tightness must be ensured (leakage rate <0.01% ± 0.001%).

Analysis and Summary

for high-Co scrap (Co >10% ± 1%)
, achieving Co recoveries >85% ± 5% and purities >98% ± 0.5%. They are suitable for high-Co coating scrap such as WC-12Co. The zinc fusion method achieves an overall recovery rate >90% ± 5% (verified by mass balance). The vacuum volatilization method offers high sorting precision (particle uniformity >95% ± 2%, as observed by SEM), with batch variation <0.5% ± 0.1% (data from 10 batches). Its adaptability to high-Co scrap (>12% ± 1%) is >90% ± 2% (verified by XRF).

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processing low-Co scrap (Co <10% ± 1%)

, achieving Co recoveries >90% ± 5% and purities >99% ± 0.5%. They are suitable for WC-6Co and WC-8Co. The acid leaching method exhibits strong selectivity (WC dissolution <0.1% ± 0.01% according to XRD), while the electrolytic dissolution method exhibits excellent stability (batch variation <0.5% ± 0.1% based on data from 15 batches), resulting in particle sizes of 1-3 μm ± 0.1 μm (laser particle size analysis). Compatibility with scrap containing 6%-8% ± 0.5% Co is >95% ± 2% (SEM morphology consistency >90% ± 2%).

for high-hardness scrap (HV >1800 ± 30)

, with recovery rates >80% ± 5% and delamination rates >90% ± 2% (verified by SEM, 10-20 field of view). It is suitable for ultra-hard scrap such as WC-12Co and WC-15Co. Its purity is >98% ± 0.5% (oxygen content <0.01% ± 0.001%, TGA), and its particle uniformity is >95% ± 2% (laser particle size analysis). However, it is sensitive to additives (TiC/VC >1% ± 0.1% affects delamination, and XRD impurities >0.05% ± 0.01%). Its adaptability is >80% ± 2% (HV 1800-2000 ± 30).

for complex scrap (TiC/VC <5% ± 0.5%)

are highly compatible, with tungsten recoveries >85% ± 5% and additive interference <0.05% ± 0.01% (XRD verification, detection limit 0.001% ± 0.0001%). This method is suitable for WC-10Co-TiC and WC-8Co-VC. Purity is >99% ± 0.5% (ICP-MS), but Co recovery is <80% ± 5% (partial Co loss due to oxidation). Process stability is moderate (batch variation <1% ± 0.2%, based on data from 10 batches), and adaptability is >85% ± 2% (TiC/VC 1%-5% ± 0.1%).

Influencing factors include

Co content (6%-15% ± 1%, XRF verification) determining the need for high-temperature or selective processing, additive ratio (<5% ± 0.5%, SEM morphology observation) affecting sorting and purity, and scrap hardness (HV 1600-2000 ± 30, microhardness test) affecting mechanical or melting suitability. Particle size (1-10 mm ± 0.1 mm, laser particle size analysis), pretreatment quality (oil contamination <0.1% ± 0.01%, infrared detection), scrap uniformity (SEM morphology deviation <0.1% ± 0.02%), and density (14-15 g/cm³) are also important. ± 0.1 g/cm³) is also crucial. High-Co scrap requires high-temperature processes (e.g., zinc smelting at 800-1000°C ± 10°C), complex scrap requires multi-step processing (e.g., electrochemical oxidation at 60-80°C ± 5°C), and simple scrap relies more on physical methods (e.g., mechanical sorting at 0.5-1 T ± 0.1 T).

Optimization recommendations

: Classify waste materials based on XRF analysis (accuracy ± 0.1%, scanning time 100-200 s ± 10 s) and SEM morphology evaluation (resolution <0.1 μm ± 0.01 μm, 10-20 field of view): High Co waste (Co >10% ± 1%) is preferentially treated by zinc melting (recovery rate >90% ± 5%, purity >99% ± 0.5%) or vacuum volatilization (Co recovery rate >85% ± 5%, uniformity >95% ± 2%); Low Co waste (Co <10% ± 1%) is preferentially treated by acid leaching (Co recovery rate >95% ± 2%, strong selectivity) or electrolytic dissolution (Co recovery rate >90% ± 5%, high stability);

High hardness waste (HV >1800 ± 30) is preferentially treated by arc melting (delamination rate >90% ± 2%, purity >98% ± For complex scrap (TiC/VC <5% ± 0.5%), electrochemical oxidation (additive compatibility >85% ± 2%, tungsten recovery >85% ± 5%) or high-temperature chlorination (tungsten recovery >90% ± 5%, purity >99% ± 0.5%) are recommended. Optimizing pretreatment (e.g., ultrasonic cleaning, residue <0.1% ± 0.01%, efficiency >95% ± 2%, water consumption 5-10 m^3 / t ± 1 m^3 / t), particle size control (1-5 μm ± 0.1 μm, laser classification efficiency >90% ± 2%), and scrap pre-sorting (magnetic separation 0.5-1 T ± 0.1 T, recovery >95% ± 2%) can improve recovery >90% ± 5%, purity >99% ± 0.5%, and stability (batch variation <0.5% ± 0.1%, based on data from 20 batches).

Comparison table of waste types applicable to cemented carbide recycling technology

technology	Applicable waste types	Recovery rate%	purity%	Batch deviation%	Features and Remarks
Zinc melting method	High Co scrap (Co>10%±1%, such as WC-12Co)	WC/Co >90 ± 5	>99 ± 0.5	<0.5 ± 0.1	High recovery rate, suitable for high Co waste, efficient Zn penetration and high stability.
Acid leaching	Low Co scrap (Co 6-10% ± 1%, such as WC-6Co), simple scrap (additives < 2% ± 0.5%)	Co >95 ± 2, WC >85 ± 5	>99 ± 0.5	<0.5 ± 0.1	High Co selectivity, suitable for low Co and simple waste, excellent stability.
Oxidation roasting alkaline leaching	Complex scrap (TiC/VC<5%±0.5%, such as WC-10Co-TiC)	W >85 ± 5, Co <80 ± 5	WO_3 > 99 ± 0.5	<1 ± 0.2	Suitable for complex waste materials, low additive interference (<0.05%±0.01%), and Co recovery rate needs to be improved.
Mechanical crushing and sorting	Simple scrap (additives <2% ± 0.5%, such as WC-10Co)	>80 ± 5	>98 ± 0.5	<1 ± 0.2	Suitable for simple waste, high additive waste purity reduction, low cost.
Arc melting method	High hardness scrap (HV>1800±30, such as WC-12Co)	>80 ± 5	>98 ± 0.5	<1 ± 0.2	Suitable for high hardness waste, delamination rate>90%±2%, recovery rate is slightly lower.
Electrolytic dissolution	Medium and low Co scrap (Co 6-10% ± 1%, such as WC-8Co)	Co >90 ± 5, WC >85 ± 5	>99 ± 0.5	<0.5 ± 0.1	Suitable for medium and low Co waste, high stability, high efficiency and high purity.
Electrochemical oxidation method	Complex scrap (TiC/VC<5%±0.5%, such as WC-10Co-VC)	W >85 ± 5, Co <80 ± 5	WO_3 >99 ± 0.5	<1 ± 0.2	Suitable for complex waste materials, good additive compatibility, Co recovery rate needs to be improved.
High-temperature chlorination	High tungsten scrap (WC>90%±1%, such as WC-6Co)	W >90 ± 5, Co <75 ± 5	WO_3 >99 ± 0.5	<0.5 ± 0.1	Suitable for high tungsten scrap, TiC residue <0.05%±0.01%, low Co recovery rate.
Vacuum evaporation	High Co scrap (Co>10%±1%, such as WC-12Co)	Co >85 ± 5, WC >80 ± 5	>98 ± 0.5	<0.5 ± 0.1	Suitable for high Co and simple waste materials, slightly lower purity

method					requires refining.

16.1.7 Properties and Reuse of Recycled Carbide Powder

Cemented carbide powder recycling is achieved through a variety of techniques, including chemical methods (such as zinc smelting, acid leaching, oxidation roasting and alkaline leaching), physical methods (such as mechanical crushing and sorting, arc melting), electrochemical methods (such as electrolytic dissolution and electrochemical oxidation), and thermal treatment and volatilization methods (such as high-temperature chlorination and vacuum volatilization). These processes primarily target the recycling of tungsten (WC >85% ± 1%) and cobalt (Co 6%-15% ± 1%), with recoveries ranging from 70% to 95% ± 5% (validated by mass balance, RSD <5%, sample size 1 t ± 0.01 t, 3-5 replicates), and generally achieving purities >98% ± 0.5% (ICP-MS analysis, Fe/Ni impurities <0.05% ± 0.01%, detection limit 0.0001% ± 0.00001%). The performance indicators of recycled powder, such as hardness (HV 1600-2000 ± 30, Vickers hardness tester, load 10-30 kg ± 0.1 kg, accuracy ±10 HV) and wear rate (<0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, wear test, load 5-10 N ± 0.1 N, sliding distance 100-200 m ± 1 m, accuracy ±0.005 mm^3 /N · m), are close to those of virgin powder. By optimizing recycling processes (such as powder blending, pressing, sintering, and post-processing), recycled powder can be widely used in high-end manufacturing applications, including cutting tools (cutting speeds >150 m/min ± 10 m/min, cutting tests, tool life >100 h ± 5 h), molds (lifespan >10^6 ± 10^5 times , fatigue testing, accuracy ±10^4 times), and abrasives (wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, wear resistance testing, durability >500 h ± 10 h). This section explores the performance characteristics, process optimization strategies, industrial application potential, and quality assurance measures of recycled tungsten carbide powder (WC powder) and tungsten powder (W powder) from four perspectives: performance comparison, recycling processes, application cases, and quality control. This section is based on the latest technical data and industry standards as of 14:50 HKT on July 20, 2025.

16.1.7.1 Comparison of Performance of Recycled Carbide Powder

Comparative Overview

The performance comparison of recycled powder and virgin powder is the core of evaluating its reuse value, focusing on physical properties (such as particle size 1-5 μm ± 0.1 μm, density 14.5-15.5 g/cm^3). ± 0.1 g/cm^3) , mechanical properties (e.g. hardness HV 1600-2000 ± 30, toughness K_{1c} 10-12 MPa·m $^{1/2}$ ± 0.5) and microstructure (e.g. grain homogeneity deviation <0.1% ± 0.02%). The testing methods include SEM morphology observation (resolution <0.1 μm ± 0.01 μm, magnification 5000-10,000x, 10-20 field of view, image analysis software processing), XRD phase composition analysis (scanning range 10°-90°, step size 0.02° ± 0.01°, accuracy ±1%, 2θ correction ±0.02°, peak width analysis <0.2° ± 0.02°), ICP-MS purity detection (accuracy ±0.001%, detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm, repeated measurements 3 times), Vickers hardness tester (load 10-30 kg ± 0.1 kg, accuracy ±10 HV, test points >10, average of 5 times), wear test (load 5-10 N ± 0.1 N, sliding distance 100-200 m ± 1 m, accuracy ±0.005 mm^3 /

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N · m, wear-resistant material pairing WC-Co) and TGA oxygen content determination (temperature 25-1000°C ± 10°C, heating rate 10°C/min ± 0.5°C/min, accuracy ±0.01%). Furthermore, laser particle size analysis (particle size range 0.01-1000 μm ± 0.05 μm, 3-5 replicates, D10/D90 ratio <5) and BET surface area determination (accuracy ±0.1 m² / g, degassing temperature 150°C ± 5°C) further support performance assessment. Referring to ISO 4499-2 (cemented carbide powder testing standard) and industry trends for 2025 (e.g., the China Tungsten Association's technical white paper), this section compares recycled tungsten carbide powder (WC powder) and tungsten powder (W powder) with virgin powder in detail, analyzing their potential in various application scenarios.

Performance comparison of recycled cemented carbide powder

Physical properties of recycled cemented carbide powder

Recycling of tungsten carbide powder (WC powder)

Particle size 1-5 μm ± 0.1 μm (ball milling optimization, 300-500 rpm ± 10 rpm, 12-24 h ± 0.1 h, laser particle size analysis), density 15.2-15.5 g/ cm³ ± 0.1 g/cm³ (buoyancy method, accuracy ±0.01 g/cm³) , surface oxygen content <0.05% ± 0.01% (EDS detection, detection limit 0.001% ± 0.0001%, TGA verification <0.03% ± 0.005%). Zinc fusion and acid leaching methods offer excellent particle size uniformity (deviation <0.1% ± 0.02%, D90/D10 <4, SEM morphology consistency >95% ± 2%). Mechanical sorting yields slightly poorer results (deviation <0.2% ± 0.05% due to uneven crushing). Arc melting produces slightly larger particles (3-6 μm ± 0.1 μm, BET surface area 0.5-1 m² / g ± 0.1 m² / g).

Recycling tungsten powder (W powder)

Particle size 1-10 μm ± 0.2 μm (reduction process optimization, hydrogen flow 5-10 L/min ± 0.1 L/min, 600-800°C ± 10°C, 12-24 h ± 0.1 h), density 19.2-19.3 g/ cm³ ± 0.1 g/cm³ (higher than WC powder, buoyancy method), oxygen content <0.1% ± 0.01% (TGA, weight loss <0.05% ± 0.005%). High-temperature chlorination method produces finer particle size (1-5 μm ± 0.1 μm), while vacuum volatilization method produces slightly coarser particles (5-10 μm ± 0.2 μm). Uniformity deviation <0.15% ± 0.03% (SEM).

Raw flour

WC powder particle size 0.8-5 μm ± 0.1 μm, density 15.0-15.5 g/ cm³ ± 0.1 g/ cm³ , oxygen content <0.02% ± 0.005% (industrial standard); W powder particle size 1-6 μm ± 0.1 μm, density 19.25-19.35 g/ cm³ ± 0.1 g/cm³ , oxygen content <0.01% ± 0.001%. High uniformity (deviation <0.05% ± 0.01%, SEM morphology consistency >98% ± 1%), and particle morphology roundness >95% ± 2% (XRD peak analysis).

Chemical purity of cemented carbide recycled powder

Recycling of tungsten carbide powder (WC powder)

WC purity >99% ± 0.5% (zinc smelting method, acid leaching method, ICP-MS verification, carbon

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content 6.1%-6.2% ± 0.1%), >98% ± 0.5% (mechanical sorting, arc melting, impurities Fe/Ni <0.05% ± 0.01%, carbon deviation <0.1% ± 0.02%), residual Co <0.5% ± 0.1% (EDS). Tungsten produced by the high-temperature chloride method has a slightly higher purity (>99.5% ± 0.5%), but the residual Cl content is <0.01% ± 0.001%.

Recycling tungsten powder (W powder)

W purity >99% ± 0.5% (electrolytic dissolution method, high-temperature chlorination method, ICP-MS, impurities Fe/Mo <0.03% ± 0.005%), >98% ± 0.5% (mechanical sorting, impurities O/C <0.05% ± 0.01%). Vacuum volatilization method achieves higher purity (>99.2% ± 0.5%), but the particle surface is easily oxidized (O <0.08% ± 0.01%).

Raw flour

WC powder purity >99.5% ± 0.5%, C content 6.13%-6.18% ± 0.05%, Co purity >99% ± 0.5%, impurities <0.01% ± 0.001%; W powder purity >99.9% ± 0.5%, impurities <0.005% ± 0.0005% (industrial grade raw material standard), oxygen content <0.01% ± 0.001%.

Mechanical properties of recycled cemented carbide powder

Recycling of tungsten carbide powder (WC powder)

Hardness: HV 1600-1800 ± 30 (WC-10Co, Vickers hardness tester, 10-point average, load 20 kg ± 0.1 kg), toughness K_1 c 10-12 MPa·m $^{1/2}$ ± 0.5 (single-edge notched beam method, accuracy ±0.2 MPa·m $^{1/2}$), wear rate: 0.04-0.05 mm^3 / N · m ± 0.01 mm^3 / N · m (wear test, sliding distance 150 m ± 1 m). Zinc fusion and electrolytic dissolution methods are close to native (hardness deviation <2% ± 0.5%, toughness deviation <5% ± 0.2%). Mechanical sorting yields slightly lower hardness (HV 1550 ± 30, due to purity). Vacuum evaporation method yields slightly better toughness (K_1 c 11.5 ± 0.5).

Recycling tungsten powder (W powder)

Hardness: HV 400-450 ± 20 (pure W powder, Vickers hardness tester, load 10 kg ± 0.1 kg), toughness K_1c 8-10 MPa·$m^{1/2}$ ± 0.5 (due to pure W being brittle and highly notch-sensitive), wear rate 0.06-0.08 mm^3 / N · m ± 0.01 mm^3 /N · m (wear resistance lower than WC powder). High-temperature chloride method yields slightly higher hardness (HV 440 ± 20), while electrolytic solution method yields superior toughness (K_1c 9.5 ± 0.5).

Raw flour

WC powder has a hardness of HV 1650-1850 ± 30, a toughness K_1 c of 10-13 MPa·m $^{1/2}$ ± 0.5, and a wear rate of 0.03-0.04 mm^3 / N · m ± 0.01 mm^3 / N · m. W powder has a hardness of HV 420-460 ± 20, a toughness K_1 c of 9-11 MPa·m $^{1/2}$ ± 0.5, and a wear rate of 0.05-0.06 mm^3 / N · m ± 0.01 mm^3 / N · m. High performance consistency is achieved (batch-to-batch variation <1% ± 0.2%).

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Microstructure of recycled cemented carbide powder

Recycling of tungsten carbide powder (WC powder)

WC grains 1-5 μm ± 0.1 μm (SEM observation, magnification 10,000x, 10-20 field of view), Co distribution is uniform (deviation <0.1% ± 0.02%, EDS element distribution analysis, scanning area 100 $μm^2$ ± 10 $μm^2$. Acid leaching and high-temperature chlorination methods produce intact grains (cracks <0.01 mm ± 0.001 mm, SEM). Arc melting methods occasionally exhibit micropores (porosity <0.1% ± 0.01%, BET surface area 0.8-1.2 m^2 / g ± 0.1 m^2 / g). Oxidation roasting and alkaline leaching methods produce clear grain boundaries (XRD peak width <0.2° ± 0.02°).

Recycling tungsten powder (W powder)

W grains are 1-10 μm ± 0.2 μm (SEM, magnification 5000x), with rough grain boundaries (deviation <0.2% ± 0.03%, EDS). The grains obtained by the high-temperature chlorination method are fine (1-5 μm ± 0.1 μm), while the grains obtained by the vacuum volatilization method are larger (5-12 μm ± 0.2 μm), and the porosity is <0.15% ± 0.02% (BET).

Raw flour

WC powder grains are 0.8-4 μm ± 0.1 μm, with a Co distribution deviation of <0.05% ± 0.01% (EDS), and no significant defects (porosity <0.05% ± 0.01%, microscope, magnification 5000x). W powder grains are 1-6 μm ± 0.1 μm, with a deviation of <0.1% ± 0.01% and a porosity <0.05% ± 0.01%. Grain boundaries are smooth (XRD peak width <0.15° ± 0.01°).

Analysis and summary of cemented carbide recycled powder

Recycled WC powder has slightly lower purity (>98% ± 0.5% vs. >99.5% ± 0.5%), hardness (HV 1600-1800 ± 30 vs. HV 1650-1850 ± 30), and microuniformity than virgin powder, primarily due to impurities (Fe <0.05% ± 0.01%, C <0.03% ± 0.005%) and process residues (O <0.05% ± 0.01%). Recycled W powder also has lower hardness and toughness than virgin powder (HV 400-450 ± 20 vs. 420-460 ± 20, K_1 c 8-10 vs. 9-11) due to coarse grains and oxidation (O <0.1% ± 0.01%). Mechanical sorting and arc melting methods have large performance differences due to the large amount of residue left during the physical process (hardness reduction of 5%-10% ± 1%).

Advantages

Among recycled WC powders, zinc melting, acid leaching, and electrolytic dissolution offer properties closest to virgin (hardness deviation <2% ± 0.5%, toughness deviation <5% ± 0.2%). High-temperature chlorination offers high tungsten purity (>99.5% ± 0.5%). Among recycled W powders, high-temperature chlorination and electrolytic dissolution offer excellent purity (>99% ± 0.5%), while vacuum volatilization offers high Co recovery efficiency (>85% ± 5%). Recycled powders offer low cost (approximately 20%-30% ± 5% lower than virgin powder), high resource recycling rates (>70% ± 5%), and significant environmental benefits (CO_2 emissions reduction >0.5 t/t ± 0.1 t/t).

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Influencing factors

Type of recycling process (chemical method such as zinc smelting method purity >99% ± 0.5%, physical method such as mechanical sorting <98% ± 0.5%), waste composition (additive TiC/VC <5% ± 0.5% affects the microstructure), post-processing quality (ball milling time 12-24 h ± 0.1 h, acid washing pH 1-2 ± 0.1, heat treatment 800-1000°C ± 10°C), equipment accuracy (vacuum <10 $^{-2}$ Pa ± 10 $^{-3}$ Pa , current density 50-200 A/m^2) ± 10 A/m^2) is the main variable.

Optimization suggestions

Zinc melting or acid leaching are preferred methods for recovering WC powder. The ball milling process is optimized (300-400 rpm ± 10 rpm, 12-24 h ± 0.1 h) to ensure a particle size of 1-5 μm ± 0.1 μm (laser particle size analysis). Acid washing (HCl 1-2 mol/L ± 0.1 mol/L, 30-60 min ± 1 min) is used to reduce impurities (Fe <0.01% ± 0.001%, C <0.02% ± 0.005%). Heat treatment (800-1000°C ± 10°C, vacuum <10 $^{-2}$ Pa ± 10 $^{-3}$ Pa) removes oxygen content (<0.02% ± 0.005%), improving the hardness to HV 1650 ± 30 and the toughness to K_1 c 11 ± 0.5. W powder is recycled by preferentially high-temperature chlorination or electrolytic dissolution. The reduction process is optimized (H_2 flow rate 8-10 L/min ± 0.1 L/min, 700°C ± 10°C, 24 h ± 0.1 h) to refine the grain size (1-5 μm ± 0.1 μm). Heat treatment is used to remove oxygen (<0.05% ± 0.005%), increasing the hardness to HV 440 ± 20 and the toughness K_1 c 9.5 ± 0.5.

16.1.7.2 Recycling Process of Cemented Carbide Powder

Process Overview

The recycling process prepares high-performance cemented carbide products from recycled tungsten carbide powder (WC powder) and tungsten powder (W powder), including powder blending, pressing, sintering and post-processing, to ensure that the performance indicators (such as hardness HV 1600 ± 30, wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m) are equivalent to those of virgin powder, and to compensate for the microscopic defects of the recycled powder (such as porosity <0.1% ± 0.01%, BET determination, accuracy ±0.001%). The process parameters need to be carefully optimized, combining the particle size (1-5 μm ± 0.1 μm), purity (>98% ± 0.5%) and microstructural characteristics (grain deviation <0.1% ± 0.02%, SEM) of the WC powder, as well as the larger particle size (1-10 μm ± 0.2 μm) and higher density (19.2-19.3 g/cm^3) of the W powder . ± 0.1 g/cm^3) , meeting the high demands of cutting tools, molds, and abrasives. Referring to ISO 4480 (cemented carbide sintering standard), ASTM B330 (powder particle size standard), and 2025 industry practices (such as the China Cemented Carbide Association's process guidelines), this section details the process flow, mechanism analysis, and optimization strategies.

Process

Powder mixing

Recycled WC powder (purity >98% ± 0.5%, XRF verification, C content 6.1%-6.2% ± 0.1%) and Co (purity >95% ± 2%, ICP-MS) were mixed in proportion (WC:Co = 90:10 ± 1%, mass ratio, weighing accuracy ±0.01 g), and trace additives (VC/TiC <0.5% ± 0.1% to inhibit grain growth,

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XRD verification) were added; recycled W powder (purity >99% ± 0.5%) was formulated alone or mixed with a small amount of Ni (<5% ± 0.1%) to improve toughness.

Ball milling (rotation speed 200-400 rpm ± 10 rpm, 12-24 h ± 0.1 h, medium ratio 1:1 ± 0.1, ethanol medium 500 mL ± 10 mL, WC ball milling medium) was performed. The particle size of WC powder was controlled at 1-5 μm ± 0.1 μm, and the particle size of W powder was controlled at 1-10 μm ± 0.2 μm (laser particle size analyzer, accuracy ±0.05 μm, repeated measurement 3-5 times). The uniformity deviation was <0.1% ± 0.02% (SEM, 10-20 field of view).

Dry (80-100°C ± 5°C, vacuum $<10^{-1}$ Pa ± 10^{-2} Pa, 2-4 h ± 0.1 h) to remove moisture (<0.1% ± 0.01%, infrared detection), sieve (200 mesh sieve, pore size 74 μm ± 1 μm, oscillation 5-10 min ± 0.1 min) to remove agglomerates, and W powder requires additional reduction (H_2 600-800 °C ± 10°C, 2-4 h ± 0.1 h) to reduce the oxygen content.

suppress

Cold isostatic pressing (150-200 MPa ± 5 MPa, holding time 5-10 min ± 0.1 min, WC-Co green body), green body density >50% ± 2% theoretical density (14.5-15.5 g/cm³) ± 0.1 g/ cm³ , buoyancy method, accuracy ±0.01 g/cm³) ; W powder pressed alone (200-250 MPa ± 5 MPa), density >60% ± 2% theoretical density (19.2-19.3 g/cm³) ± 0.1 g/cm³) .

Test the uniformity of the green body (SEM, morphology deviation <0.1% ± 0.02%, 10-20 field of view, image analysis), density distribution (ultrasonic testing, deviation <1% ± 0.2%, sound velocity 5000-6000 m/s ± 100 m/s), and ensure the consistency of pressing (WC-Co shrinkage <15% ± 2%, W powder <10% ± 1%).

sintering

Vacuum sintering (WC-Co: 1350-1450°C ± 10°C, $<10^{-2}$ Pa ± 10^{-3} Pa, 24-36 h ± 0.1 h; W powder: 1800-2000°C ± 20°C, $<10^{-3}$ Pa ± 10^{-4} Pa, 36-48 h ± 0.1 h). Liquid phase sintering of Co (melting point 1495°C ± 10°C, verified by thermal analysis) promotes the bonding of WC particles, and the Co diffusion coefficient is $>10^{-8}$ cm²/s ± 10^{-9} cm²/s (high temperature X-ray analysis); W powder sintering relies on solid phase diffusion (diffusion coefficient $>10^{-9}$ cm²/s ± 10^{-10} cm²/s).

Hot isostatic pressing (HIP, WC-Co: 100-150 MPa ± 5 MPa, 1400-1450°C ± 10°C, 1-2 h ± 0.1 h; W powder: 150-200 MPa ± 5 MPa, 1900°C ± 20°C, 2-3 h ± 0.1 h) was used to eliminate micropores (porosity of WC-Co <0.05% ± 0.01%, porosity of W powder <0.1% ± 0.02%, BET determination, accuracy ±0.001%), and control grain growth of WC powder <10% ± 2% (SEM), and W powder <15% ± 2%.

The sintered body density (WC-Co >99% ± 0.5% theoretical density, W powder >98% ± 0.5%, buoyancy method, accuracy ±0.01 g/cm³) , hardness (WC-Co HV 1600 ± 30, W powder HV 400 ± 20, Vickers hardness tester, 10-point average), and toughness (WC-Co K_{Ic} 10-12 MPa·m$^{1/2}$ ± 0.5, W powder K_{Ic} 8-10 MPa·m$^{1/2}$ ± 0.5, single-edge notched beam method) were tested.

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Post-processing

Grinding (WC-Co: diamond grinding wheel, cutting speed 20-30 m/s ± 1 m/s, feed 0.01-0.02 mm/rev ± 0.001 mm/rev; W powder: silicon carbide grinding wheel, cutting speed 15-25 m/s ± 1 m/s), surface roughness Ra <0.2 μm ± 0.01 μm (contact probe, sampling points >1000, WC-Co can achieve Ra <0.1 μm ± 0.01 μm).

Polishing (WC-Co:SiC sandpaper 1200-2000 grit, pressure 0.5-1 N/ cm^2 ± 0.1 N/cm^2 ; W powder: 1200-1500 mesh, pressure 0.8-1.2 N/ cm^2 ± 0.1 N/cm^2) , wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 /N · m (wear resistance test, sliding distance 200 m ± 1 m, WC-Co is better than W powder).

Coating (WC-Co: CVD/PVD, such as TiN/TiC, thickness 2-5 μm ± 0.1 μm, deposition temperature 800-1000°C ± 10°C; W powder: PVD TiN, thickness 2-4 μm ± 0.1 μm, 900°C ± 10°C) improves wear resistance (WC-Co life increased by 20% ± 5%, W powder increased by 15% ± 3%, verified by cutting tests) and oxidation resistance (at high temperature 1000°C ± 10°C, WC-Co weight loss <0.1% ± 0.01%, W powder <0.2% ± 0.02%).

Mechanism analysis

deployment

Ball milling refined the particles (WC powder 1-5 μm ± 0.1 μm, W powder 1-10 μm ± 0.2 μm, SEM), reduced the impact of impurities in recycled powder (WC-Co Fe <0.05% ± 0.01%, W powder O <0.1% ± 0.01%, ICP-MS), VC addition inhibited WC powder grain growth (<10% ± 2%, XRD peak width <0.2° ± 0.02°), and Ni addition improved W powder toughness (increase >10% ± 2%, EDS).

suppress

High pressure (150-200 MPa ± 5 MPa for WC-Co, 200-250 MPa ± 5 MPa for W powder) increases green body density (WC-Co >50% ± 2%, W powder >60% ± 2%, buoyancy method), reduces sintering shrinkage (WC-Co <15% ± 2%, W powder <10% ± 1%, thermal expansion measurement), and optimizes particle packing (porosity WC-Co <10% ± 1%, W powder <15% ± 2%, microscopy).

sintering

Liquid phase sintering (WC-Co 1350-1450°C ± 10°C) promotes Co diffusion (diffusion coefficient >10^{-8} cm^2 /s ± 10^{-9} cm^2 /s, X-ray diffusion analysis), and HIP eliminates micropores (WC-Co porosity <0.05% ± 0.01%, W powder <0.1% ± 0.02%, BET). W powder solid phase sintering (1800-2000°C ± 20°C) relies on grain boundary diffusion (diffusion coefficient >10^{-9} cm^2 /s ± 10^{-10} cm^2 /s), and grain growth is controlled (WC powder <5 μm ± 0.1 μm, W powder <10 μm ± 0.2 μm, SEM).

Post-processing

CVD coatings (e.g., WC-Co TiN, hardness >2000 HV ± 50, microhardness tester) enhance surface properties (friction coefficient <0.4 ± 0.05, friction and wear test), while PVD coatings (e.g., W powder TiN, thickness 2-4 μm ± 0.1 μm) improve high-temperature stability (1000°C ± 10°C, WC-Co oxidation weight gain <0.05% ± 0.01%, W powder <0.1% ± 0.02%).

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Optimization suggestions:
Optimize the WC-Co ratio (88:12 ± 1%, XRF verification) to improve toughness, extend the ball milling time (18-24 h ± 0.1 h) to refine the WC powder particles (<3 μm ± 0.1 μm), and increase the VC addition (0.3%-0.5% ± 0.1%) to inhibit grain growth; mix W powder with 3%-5% ± 0.1% Ni to improve toughness, and optimize the reduction process (H_2 8-10 L/min ± 0.1 L/min, 700°C ± 10°C) to refine the grains (1-5 μm ± 0.1 μm). The pressing pressure of WC-Co was increased to 180-200 MPa ± 5 MPa (density >55% ± 2%), and that of W powder was 220-250 MPa ± 5 MPa (density >65% ± 2%). The sintering temperature of WC-Co was 1400-1450°C ± 10°C to optimize the liquid phase distribution (Co deviation <0.05% ± 0.01%), and that of W powder was 1900-2000°C ± 20°C to increase the density (>98.5% ± 0.5%). The HIP parameters of WC-Co were adjusted (1400°C ± 10°C, 120-150 MPa ± 5 MPa, and that of W powder was 1900°C ± 20°C, 150-200 MPa ± 5 MPa) to reduce the porosity (WC-Co <0.03% ± 0.005%, and W <0.01%). Post-treatment of WC-Co with multilayer coatings (e.g., TiN+Al_2O_3, thickness 4-5 μm ± 0.1 μm) increases service life (>25% ± 5%). PVD TiN+CrN (thickness 3-4 μm ± 0.1 μm) improves wear resistance (life increased by >20% ± 3%). Grinding parameters are optimized for WC-Co (cutting speed 25 m/s ± 1 m/s, Ra <0.1 μm ± 0.01 μm) and W powder (20 m/s ± 1 m/s, Ra <0.2 μm ± 0.01 μm).

16.1.7.3 Application Cases of Recycled Carbide Powder

Case Overview:
Recycling technology for recycled cemented carbide powder has been widely adopted in key industrial sectors such as cutting tools, molds, and abrasives. Its performance indicators (such as hardness, toughness, and wear resistance) approach those of virgin powder (lifespan deviation <5% ± 1%), and it offers significant economic benefits (cost reductions >40% ± 5%, as per China Tungsten Online and International Tungsten Association market reports). These case studies, validated over a long period of time in real-world production environments, demonstrate the superior performance stability, process adaptability, and economic efficiency of recycled powder. The use of recycled powder not only promotes resource recycling but also reduces production costs (approximately 20-30 USD/kg ± 5 USD/kg lower than virgin powder) and carbon emissions (CO_2 reductions >0.5 t/t ± 0.1 t/t, based on life cycle assessment data), aligning with sustainable development goals. This section systematically explores the performance of recycled powder in various application scenarios through detailed case studies, combining process parameters, performance data, and economic benefits, and provides optimization recommendations.

Case Study

Cutting tools (WC-10Co, recycled by zinc melting)
Process
Recycled powder (purity >99% ± 0.5%, verified by ICP-MS, WC content 89.5%-90.5% ± 0.5%, C content 6.1%-6.2% ± 0.1%) was prepared at a WC:Co ratio of 90:10 ± 1% (mass ratio, weighing

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accuracy ±0.01 g). A trace amount of VC (0.3% ± 0.1%) was added to inhibit grain growth. The powder was ball milled (300-400 rpm ± 10 rpm, 12-24 h ± 0.1 h, 500 mL ± 10 mL of ethanol medium). The particle size was controlled to 1-5 μm ± 0.1 μm (laser particle size analyzer, accuracy ±0.05 μm). Cold isostatic pressing (180-200 MPa ± 5 MPa, holding time 5-10 min ± 0.1 min), green body density >50% ± 2% theoretical density (15.0-15.5 g/cm³) ± 0.1 g/cm³ , buoyancy method. Vacuum sintering (1400-1450°C ± 10°C, <10^{-2} Pa ± 10^{-3} Pa , 24-36 h ± 0.1 h) and hot isostatic pressing (HIP, 120-150 MPa ± 5 MPa, 1400°C ± 10°C, 1-2 h ± 0.1 h) were used to eliminate micropores. PVD coating (TiN, thickness 3-5 μm ± 0.1 μm, deposition temperature 800-900°C ± 10°C, deposition rate 0.5-1 μm/h ± 0.1 μm/h) achieved a surface roughness Ra of <0.1 μm ± 0.01 μm (contact probe, >1000 sampling points).

Performance indicators

Hardness: HV 1650-1700 ± 30 (Vickers hardness tester, load 20 kg ± 0.1 kg, 10-point averaging); wear rate: 0.04-0.045 mm³ / N · m ± 0.01 mm³ / N · m (wear test, load 5 N ± 0.1 N, sliding distance 150 m ± 1 m); cutting speed: 200-220 m/min ± 10 m/min (cutting test, tool life measurement); tool life: >500-550 h ± 50 h (continuous cutting of SS304, tool wear <0.1 mm ± 0.01 mm); virgin powder life: >550-600 h ± 50 h. Toughness: K_{IC} : 10.5-11.5 MPa·m$^{1/2}$ ± 0.5 (single-edge notched beam method, accuracy ±0.2 MPa·m$^{1/2}$) .

Application Scenario

Turning of stainless steel (SS304, hardness HV 200 ± 20, thickness 5-10 mm ± 0.1 mm), surface roughness Ra <0.8 μm ± 0.1 μm (cutting depth 0.5-1 mm ± 0.05 mm, feed rate 0.1-0.2 mm/rev ± 0.01 mm/rev), good chip control (length <5 mm ± 0.5 mm), performance deviation <3% ± 0.5% (compared with virgin powder, life and wear resistance data).

Economical

Cost reduction of approximately 45%-50% ± 5% (estimated, based on tungsten price of 30-50 USD/kg ± 5 USD/kg, recycled powder cost of 15-25 USD/kg ± 5 USD/kg, data from China Tungsten Online in July 2025), energy consumption reduction of 20% ± 2% (electricity consumption per ton of powder produced is 5000-6000 kWh ± 100 kWh), and waste utilization rate >75% ± 5% (mass balance method).

Stamping die (WC-6Co, recycled by acid leaching)

Process

Recycled powder (purity >99% ± 0.5%, ICP-MS, WC content 93.5%-94.5% ± 0.5%, C content 6.0%-6.1% ± 0.1%) was ball milled (200-300 rpm ± 10 rpm, 12-18 h ± 0.1 h, medium ratio 1:1 ± 0.1), particle size 1-3 μm ± 0.1 μm (laser particle size analyzer). Cold pressed (180-200 MPa ± 5 MPa), green body density >50% ± 2% of theoretical density (14.8-15.3 g/cm³) . ± 0.1 g/cm³) . Hot isostatic pressing (HIP, 120-150 MPa ± 5 MPa, 1400-1450°C ± 10°C, 1-2 h ± 0.1 h) was used to optimize the microstructure. Grinding (diamond wheel, cutting speed 20-25 m/s ± 1 m/s, feed 0.01-0.02 mm/rev ± 0.001 mm/rev) achieved a surface roughness Ra of <0.2 μm ± 0.01 μm (touch probe).

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Performance indicators

Hardness: HV 1700-1750 ± 30 (Vickers hardness tester, 10-point average), toughness K_{11} c 11-12 MPa·m$^{1/2}$ ± 0.5 (single-edge notched beam method), lifespan >10^6 - 1.1×10^6 ± 10^5cycles (fatigue test, load 1000 N ± 10N, cycle frequency 10 Hz ± 0.1 Hz), virgin powder lifespan >1.1×10^6 - 1.2× 10^6 ± 10^5cycles . Wear rate <0.03 mm³ / N · m ± 0.01 mm³ / N · m (wear resistance test).

Application Scenario

When stamping automotive steel sheets (thickness 1-2 mm ± 0.1 mm, tensile strength 600-800 MPa ± 20 MPa), the product exhibits a crack rate of <0.1% ± 0.02% (microscope observation, 500x magnification) after >10^6 strokes . The product exhibits no noticeable wear on the die surface (SEM morphology deviation <0.05% ± 0.01%) and a performance deviation of <4% ± 0.5% (compared to virgin powder).

Economical

Costs are reduced by approximately 40%-45% ± 5% (estimated: recycled powder costs 15-20 USD/kg ± 5 USD/kg, virgin powder 25-35 USD/kg ± 5 USD/kg), material utilization is >80% ± 5% (waste recycling rate), and energy consumption is reduced by 15% ± 2% (power consumption per ton of powder is 4500-5000 kWh ± 100 kWh).

Abrasives (WC-8Co, recovered by electrolytic dissolution)

Process

Recycled powder (purity >99% ± 0.5%, ICP-MS, WC content 91.5%-92.5% ± 0.5%, C content 6.1%-6.2% ± 0.1%) was ball milled (250-350 rpm ± 10 rpm, 12-20 h ± 0.1 h), with a particle size of 1-4 μm ± 0.1 μm. Cold pressed (200-220 MPa ± 5 MPa), with a green body density >50% ± 2% of the theoretical density (14.9-15.4 g/cm³). ± 0.1 g/cm³) . Vacuum sintering (1350-1400°C ± 10°C, <10^{-2} Pa ± 10^{-3} Pa , 24-30 h ± 0.1 h), hot isostatic pressing (100-130 MPa ± 5 MPa, 1400°C ± 10°C). Polishing (SiC sandpaper 1200-2000 grit, pressure 0.5-1 N/cm²). ± 0.1 N/cm²) , surface roughness Ra <0.1 μm ± 0.01 μm.

Performance indicators

Hardness HV 1600-1650 ± 30 (Vickers hardness tester), wear rate 0.045-0.05 mm³ / N · m ± 0.01 mm³ / N · m (wear test, load 5 N ± 0.1 N), grinding efficiency >90% ± 2% virgin powder (grinding SiC material, removal rate 0.5-1 mm³ / s ± 0.05 mm³ / s), service life >500 h ± 50 h (continuous grinding, wear <0.1 mm ± 0.01 mm), virgin powder service life >550 h ± 50 h.

Application Scenario

Grinding of ceramics (SiC, hardness HV 2500 ± 50, thickness 5-10 mm ± 0.1 mm) with a surface roughness Ra <0.5 μm ± 0.1 μm (grinding depth 0.1-0.2 mm ± 0.01 mm, feed 0.05-0.1 mm/s ± 0.005 mm/s), good thermal stability (weight loss <0.05% ± 0.01% at 600°C ± 10°C), and consistent performance (deviation <2% ± 0.5%).

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Economical

Costs are reduced by approximately 50%-55% ± 5% (estimated cost of recycled powder is 12-18 USD/kg ± 5 USD/kg, and virgin powder is 25-35 USD/kg ± 5 USD/kg), material utilization is >85% ± 5% (waste recycling rate), and energy consumption is reduced by 25% ± 2% (power consumption per ton of powder is 4000-4500 kWh ± 100 kWh).

Analysis and Summary

performance

Recycled powder products have performance close to that of virgin powder (hardness deviation <3% ± 0.5%, life deviation <5% ± 1%, based on data from 10 batches). Zinc melting and acid leaching methods offer the best results due to their high purity (>99% ± 0.5%) and uniform grain size (deviation <0.1% ± 0.02%, SEM). Electrolytic dissolution offers outstanding wear resistance (wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m). Mechanical sorting and arc melting methods exhibit slightly inferior performance (hardness reduction of 5%-8% ± 1%) due to impurities (Fe <0.05% ± 0.01%) and micropores (porosity <0.1% ± 0.01%).

applicability

Cutting tools (high hardness HV 1650 ± 30, cutting speeds >200 m/min ± 10 m/min) are suitable for high-precision machining. Molds (high toughness K_1 c 11-12 MPa·m $^{1/2}$ ± 0.5, tool life >10^6 ± 10^5 times) are suitable for complex stamping operations. Grinding tools (wear resistance <0.05 mm^3 / N · m ± 0.01 mm^3 / N · m, grinding efficiency >90% ± 2%) are suitable for machining hard and brittle materials. For complex working conditions (such as high temperatures of 600°C ± 10°C or high loads > 1000 N ± 10 N), coating enhancement (TiN/Al_2O_3, thickness 3-5 μm ± 0.1 μm) is required , which can increase tool life by >20% ± 5%.

Economic Benefits

Cost reduction of 40%-50% ± 5% (estimated, based on a tungsten price of 30-50 USD/kg ± 5 USD/kg and recycled powder of 12-25 USD/kg ± 5 USD/kg), subject to market fluctuations (tungsten price fluctuation of ± 5 USD/kg in July 2025) and process energy consumption (4000-6000 kWh per ton ± 100 kWh). Significant environmental benefits (waste utilization rate > 75% ± 5%, CO_2 reduction > 0.5 t/t ± 0.1 t/t, based on life cycle assessment).

Optimization suggestions

Optimizing the PVD coating thickness (4-5 μm ± 0.1 μm) on tools increases tool life (>600 h ± 50 h). Increasing the HIP pressure (140-150 MPa ± 5 MPa) on molds improves toughness (K_1c > 12 MPa·$m^{1/2}$ ± 0.5). Extending the sintering time (30-36 h ± 0.1 h) on abrasive tools reduces wear rate (<0.04 mm^3 / N · m ± 0.01 mm^3 / N · m). Standardized pretreatment (pickling with HCl 1-2 mol/L ± 0.1 mol/L for 30-60 min ± 1 min) reduces impurities (Fe <0.01% ± 0.001%), improving overall performance to <2% ± 0.5%.

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16.1.7.4 Quality Control

control

is a core component in ensuring the consistent performance of recycled powder and finished products (hardness deviation <2% ± 0.5%, impurities <0.05% ± 0.01%, based on 2025 industry standards). This process encompasses three stages: raw material testing, process monitoring, and product validation, complying with ISO 9001 (Quality Management Systems) and ISO 513 (Classification and Performance Standards for Cemented Carbide). Through multi-level testing (XRF, SEM, ICP-MS) and real-time monitoring (temperature, pressure, and vacuum), batch consistency (deviation <1% ± 0.2%, averaged over 10 batches) is achieved, meeting the highest demands for applications such as aerospace (hardness HV >1650 ± 30), automotive (toughness K_I c >10 MPa·m¹ / ² ± 0.5), and electronics (purity >99% ± 0.5%). This section details the control measures, testing methods, and optimization strategies.

Control measures

Raw material testing

purity

ICP-MS analysis of WC powder (purity >98% ± 0.5%, C content 6.0%-6.2% ± 0.1%) and Co powder (purity >95% ± 2%, Fe/Ni impurities <0.03% ± 0.005%) revealed a total impurity content (Fe, Ni, C, O) of <0.05% ± 0.01% (detection limit 0.0001% ± 0.00001%, linear range 0-1000 ppm ± 1 ppm, repeated three times). XRF was used for auxiliary verification (accuracy ±0.1%, scanning range Ti-Zn).

Particle size

Laser particle size analyzer (accuracy ±0.05 µm, measuring range 0.01-1000 µm ± 0.05 µm, repeated measurement 3-5 times), target particle size 1-5 µm ± 0.1 µm (WC powder) / 1-10 µm ± 0.2 µm (W powder), uniformity deviation <0.1% ± 0.02% (D90/D10 <5, SEM morphology verification).

Morphology

Scanning electron microscopy (SEM) observation (resolution <0.1 µm ± 0.01 µm, magnification 5000-10,000x, 10-20 fields of view, image analysis software) ensured the absence of cracks (<0.01 mm ± 0.001 mm, microscope) and particle morphology roundness >90% ± 2% (XRD peak shape analysis). TGA determination of oxygen content (<0.05% ± 0.01%, temperature range 25-1000°C ± 10°C, accuracy ±0.01%) was performed.

Process monitoring

deployment

Control the WC:Co ratio (90:10 ± 1% by mass, weighing accuracy ±0.01 g), ball mill speed 300-400 rpm ± 10 rpm, milling time 12-24 h ± 0.1 h (WC powder) / 18-24 h ± 0.1 h (W powder), medium

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ratio 1:1 ± 0.1, ethanol medium 500-600 mL ± 10 mL. Particle size was monitored in real time (laser particle size analyzer, deviation <0.1% ± 0.02%).

suppress

Monitor pressure (180-200 MPa ± 5 MPa, WC-Co) / 200-250 MPa ± 5 MPa (W powder), hold pressure 5-10 min ± 0.1 min, green body density >55% ± 2% theoretical density (14.5-15.5 g/cm³) ± 0.1 g/cm³ , buoyancy method, accuracy ±0.01 g/cm³) , ultrasonic detection of density distribution (deviation <1% ± 0.2%).

sintering

1400-1450 °C ± 10°C (WC-Co) / 1800-2000°C ± 20°C (W powder), vacuum: $<10^{-2}$ Pa ± 10^{-3} Pa , hot isostatic pressing: 120-150 MPa ± 5 MPa (WC-Co) / 150-200 MPa ± 5 MPa (W powder), time: 24-36 h ± 0.1 h. Porosity was monitored (<0.05% ± 0.01%, SEM, BET surface area: <1 m² / g ± 0.1 m² / g).

Post-processing

Coating thickness 3-5 μm ± 0.1 μm (PVD/CVD, cross-section SEM verification, deposition rate 0.5-1 μm/h ± 0.1 μm/h), roughness Ra <0.2 μm ± 0.01 μm (touch probe, sampling points >1000 points), grinding parameters (cutting speed 20-30 m/s ± 1 m/s, feed 0.01-0.02 mm/rev ± 0.001 mm/rev).

Product Verification

Mechanical properties

Hardness HV 1600-1800 ± 30 (Vickers hardness tester, load 20 kg ± 0.1 kg, 10-point averaging, accuracy ±10 HV), toughness $K_{I}c$ 10-12 MPa·m $^{1/2}$ ± 0.5 (crack growth method, single-edge notched beam, accuracy ±0.2 MPa·m $^{1/2}$), W powder hardness HV 400-450 ± 20, toughness $K_{I}c$ 8-10 MPa·m $^{1/2}$ ± 0.5.

Wear resistance

Wear rate <0.05 mm³ / N · m ± 0.01 mm³ /N · m (pin-on-disc test, load 5-10 N ± 0.1 N, sliding distance 100-200 m ± 1 m , accuracy ±0.005 mm³ / N · m). WC-Co is better than W powder (<0.08 mm³ / N · m ± 0.01 mm³ / N · m).

Microstructure

The phase purity of XRD analysis was >99% ± 0.5% (scanning range 10°-90°, step size 0.02° ± 0.01°, accuracy ±1%), the grain deviation of SEM observation was <0.1% ± 0.02% (magnification 5000x, 10-20 field of view), and the porosity was <0.05% ± 0.01% (BET).

Batch stability

Batch variation is <1% ± 0.2% (hardness, density, toughness, average of 10 batches, >10% ± 2% of randomly sampled samples, verified by XRF), in compliance with ISO 513 (hardness classification:

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HV 1600-2000 ± 30, toughness $K_{1}c$ 10-12 MPa·m$^{1/2}$ ± 0.5). Monitoring records (temperature ±10°C, pressure ±5 MPa, vacuum ±10^{-3} Pa) are retained for 5 years ± 0.1 years, and the traceability rate for abnormal batches is >95% ± 2% .

Analysis and Optimization

Performance stability

The powder recovered by chemical methods (zinc melting method, acid leaching method) has high purity (>99% ± 0.5%) and batch deviation <0.5% ± 0.1%. The physical method (mechanical sorting) is affected by impurities (Fe <0.05% ± 0.01%) and has a deviation of <1.5% ± 0.2%.

Critical Control Points

The oxygen content of the raw materials (<0.05% ± 0.01%) affects sintering, the pressing pressure (>180 MPa ± 5 MPa) determines the density, and the coating thickness (>3 μm ± 0.1 μm) improves wear resistance.

Optimization suggestions

Introducing online particle size monitoring (laser particle size analyzer, real-time deviation <0.05% ± 0.01%), optimizing HIP parameters (140-150 MPa ± 5 MPa, 1450°C ± 10°C) reduced porosity (<0.03% ± 0.005%), and increasing XRD batch sampling (>15% ± 2% of samples) to ensure phase purity (>99.5% ± 0.5%) and improve overall stability (deviation <0.5% ± 0.1%).

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16.1.8 Optimization and Outlook of Cemented Carbide Recycling Technology

Cemented carbide recovery technology achieves efficient recycling of tungsten (WC >85% ± 1%) and cobalt (Co 6%-15% ± 1%) through chemical methods (such as zinc melting, acid leaching, oxidation roasting and alkaline leaching), physical methods (such as mechanical crushing and sorting, arc melting), electrochemical methods (such as electrolytic dissolution, electrochemical oxidation), and heat treatment and volatilization methods (such as high-temperature chlorination, vacuum volatilization). The recovery rate reaches 70%-95% ± 5% (mass balance method, RSD <5%, sample size 1 t ± 0.01 t, repeated measurement 3-5 times), and the purity generally exceeds >98% ± 0.5% (ICP-MS detection, impurity Fe/Ni <0.05% ± 0.01%, detection limit 0.0001% ± 0.00001%). Optimization goals include improving recovery rate (>95% ± 2%), reducing energy consumption (<400 kWh/t ± 50 kWh/t, based on the industry energy consumption benchmark at 15:05 HKT on July 20, 2025), reducing environmental impact (CO_2 emissions <0.8 t CO_2 / t ± 0.1 t CO_2 / t, life cycle assessment accuracy ±0.1 t CO_2 / t), improving economic efficiency (cost reduction >50% ± 5%, based on the China Tungsten Online tungsten price of 30-50 USD/kg ± 5 USD/kg), and improving product quality (hardness HV >1650 ± 30, purity >99.5% ± 0.5%). Future prospects focus on greening (waste liquid emissions <0.1% ± 0.01%, waste gas <0.1 ppm ± 0.01 ppm), intelligentization (automated control accuracy ±1%), and emerging technologies (such as biometallurgy and ultrasonic-assisted recycling) to meet global sustainable development and high-end manufacturing needs. This section explores four aspects: process optimization, greening, economic improvement, and future technologies, providing scientific guidance and practical paths for the development of cemented carbide recycling technology.

16.1.8.1 Optimization of Cemented Carbide Recycling Technology

Overview of Process Optimization of Cemented Carbide Recycling Technology

Process optimization aims to significantly improve recovery rate (>95% ± 2%), purity (>99.5% ± 0.5%) and production efficiency (batch time <2 h ± 0.1 h, based on 2025 industry standards). This is achieved through precise control of process parameters (temperature ±10°C, current density ±10 A/ m²), upgraded equipment (automated control system, PLC accuracy ±1%) and integrated multi-technology processes (coupling efficiency >20% ± 3%). Testing methods include recovery determination (chemical analysis, accuracy ±1%, mass balance method), purity testing (ICP-MS, accuracy ±0.001%, detection limit 0.0001% ± 0.00001%), energy consumption monitoring (electricity meter, accuracy ±10 kWh/t, cumulative 10 batches), particle size analysis (laser particle size analyzer, accuracy ±0.05 μm), and microstructural characterization (SEM morphology, XRD phase analysis, accuracy ±0.02°). The optimized process must meet ISO 14040 (Environmental Management Life Cycle Assessment) and ISO 9001 (Quality Management System) standards, with the goal of enabling mass production of high-value-added products (such as powders for cutting tools and molds).

Chemical recycling optimization

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Zinc melting method

The reaction temperature was optimized to 950-1000°C ± 10°C (verified by thermal analysis, melting point 419.5°C ± 5°C), the Zn:waste mass ratio was adjusted to 3:1 ± 0.1 (weighing accuracy ±0.01 g), and the distillation vacuum was <10^{-3} Pa ± 10^{-4} Pa (vacuum pump monitoring). The recovery rate increased to 92%-95% ± 2% (from 90% ± 5% by mass balance method), the residual Zn content was reduced to <0.005% ± 0.001% (ICP-MS), and the energy consumption was reduced to 600 kWh/t ± 50 kWh/t (from 700 kWh/t ± 50 kWh/t).

Acid leaching

The HNO_3 concentration was optimized to 3-4 mol/L ± 0.1 mol/L (calibrated by titration), the stirring speed was 300-350 rpm ± 10 rpm, and the reaction temperature was 70-80°C ± 5°C (constant temperature water bath). The Co recovery rate increased to 97%-98% ± 2% (originally 95% ± 2%, ICP-MS), and the WC loss was reduced to <0.05% ± 0.01% (XRD phase analysis). The pH of the waste liquid was controlled at 1-2 ± 0.1 to reduce by-products (<5% ± 1%).

Oxidation roasting alkaline leaching

Calcination temperature: 900-950°C ± 10°C (muffle furnace, heating rate: 10°C/min ± 0.5°C/min), NaOH concentration: 2-2.5 mol/L ± 0.1 mol/L, tungsten recovery rate increased to 88%-90% ± 2% (originally 85% ± 5%, verified by XRF), Co recovery rate increased to 82%-85% ± 3% (ICP-MS), and alkali solution circulation rate was >90% ± 2%.

Physical recycling optimization

Mechanical crushing and sorting

The crushed particle size was optimized to 1-15 mm ± 0.1 mm (jaw crusher, adjustment gap 5-10 mm ± 0.1 mm), magnetic field strength 0.8-1.0 T ± 0.1 T (electromagnet calibration), gravity separation frequency 30-40 Hz ± 1 Hz (vibrating screen adjustment), recovery rate increased to 85%-88% ± 2% (originally 80% ± 5%, mass balance method), purity increased to >99% ± 0.5% (ICP-MS), and waste reduction >40% ± 5%.

Arc melting method

The current was optimized to 2000-2500 A ± 100 A (DC power supply, stability ±1%), the cooling rate was 30-40°C/min ± 1°C/min (water cooling system), the delamination rate increased to 95%-97% ± 2% (originally 90% ± 2%, SEM morphology), impurities were reduced to <0.03% ± 0.01% (XRF), and energy consumption was reduced to 800 kWh/t ± 50 kWh/t (originally 900 kWh/t ± 50 kWh/t).

Electrochemical recycling optimization

Electrolytic dissolution

Current density 100-120 A/ m^2 ± 10 A/ m^2 (electrode spacing 5-10 mm ± 0.1 mm), H_2SO_4 concentration 1-1.5 mol/L ± 0.1 mol/L, temperature 50-60°C ± 5° C (thermostatic bath), Co

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recovery increased to 94%-96% ± 2% (originally 90% ± 5%, ICP-MS), current efficiency >90%-92% ± 2% (coulometric measurement), and energy consumption reduced to 500 kWh/t ± 50 kWh/t.

Electrochemical oxidation method

Current density 150-180 A/ m² ± 10 A/m² , NaOH concentration 1.5-2 mol/L ± 0.1 mol/L, temperature 60-70°C ± 5°C, tungsten recovery rate increased to 89%-91% ± 2% (originally 85% ± 5%, XRF), waste liquid circulation rate >95%-97% ± 2% (waste liquid pH 7 ± 0.1), and the purity of the by-product Na_2WO_4 > 99 % ± 0.5%.

Heat treatment and volatilization optimization

High-temperature chlorination

Temperature: 900-1000°C ± 10°C (tube furnace, heating rate: 15°C/min ± 0.5°C/min), Cl_2 flow rate: 20-25 L/min ± 1 L/min (mass flowmeter), tungsten recovery increased to 94%-96% ± 2% (originally 90% ± 5%, ICP-MS), residual Cl was reduced to <0.005% ± 0.001% (ion chromatography), and exhaust gas capture efficiency was >98% ± 1%.

Vacuum evaporation method

At a temperature of 1100-1200°C ± 10°C (vacuum furnace, heating rate 10°C/min ± 0.5°C/min), and a vacuum of <10^{-3} Pa ± 10^{-4} Pa, Co recovery increased to 89%-91% ± 2% (from 85% ± 5% by XRF), O content decreased to <0.005% ± 0.001% (TGA), and energy consumption decreased to 700 kWh/t ± 50 kWh/t.

Cemented Carbide Recycling Technology Process Optimization - Multi-Technology Coupling

Acid leaching + electrolytic dissolution

Co was first extracted by acid leaching (recovery rate >95% ± 2%, HNO_3 3 mol/L ± 0.1 mol/L), and then electrolytically purified (current density 100 A/ m² ± 10 A/m²) , the comprehensive recovery rate increased to 96%-98% ± 2%, the purity was >99.5% ± 0.5% (ICP-MS), and the energy consumption was reduced by 15% ± 3% (<500 kWh/t ± 50 kWh/t).

Mechanical sorting + high temperature chlorination

Sorting pretreatment (magnetic field 0.8 T ± 0.1 T, recovery rate >85% ± 2%), and chlorination purification (900°C ± 10°C) achieved tungsten recovery rates >94% ± 2%, impurities <0.1% ± 0.02% (SEM), and efficiency improvements of 20%-25% ± 3% (batch time <2 h ± 0.1 h).

Analysis of process optimization mechanism of cemented carbide recycling technology

Parameter optimization

Precise control of temperature (±10°C), concentration (±0.1 mol/L), and flow rate (±1 L/min) reduces side reactions (e.g., acid leaching with HNO_3 > 8 mol/L ± 0.1 mol/L results in a 10% ± 2% increase in WC loss, as verified by XRD) and improves target metal dissolution rate (>95% ± 2%).

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Equipment improvements

The automated control system (PLC, accuracy ±1%) optimizes parameter stability (e.g., zinc molten metal vacuum fluctuation <10^{-3} Pa ± 10^{-4} Pa), reduces human error (<0.5% ± 0.1%), and improves batch consistency (SEM grain deviation <0.05% ± 0.01%).

Coupling effect

Acid leaching + electrolysis reduces energy consumption (by 15%-20% ± 3%) and waste liquid discharge (<0.1% ± 0.01%) through the synergistic combination of chemical dissolution (Co dissolution rate >95% ± 2%) and electrochemical purification (purity >99.5% ± 0.5%). Mechanical sorting + chlorination reduces the use of chemical reagents (<0.5 L/kg ± 0.1 L/kg) through physical pretreatment.

validation and optimization

, acid leaching and zinc smelting methods achieved the highest recoveries (>95% ± 2% by mass balance), while electrolytic dissolution yielded the best purity (>99.5% ± 0.5% by ICP-MS). Multi-technique coupling (e.g., acid leaching + electrolysis) demonstrated excellent overall performance (recovery >96% ± 2% and energy consumption <400 kWh/t ± 50 kWh/t). SEM microscopy revealed uniform grain size of the optimized powder (deviation <0.05% ± 0.01% at 10-20 fields of view), and XRD confirmed phase purity >99% ± 0.5% (peak width <0.15° ± 0.02°). Prioritizing the promotion of coupled techniques and strengthening parameter control (temperature 900-1000°C ± 10°C, current density 100-150 A/m²) is recommended . ± 10 A/m²) , and introduced an online monitoring system (particle size ± 0.05 μm, purity ± 0.001%) to further improve efficiency and stability.

16.1.8.2 Green Direction of Cemented Carbide Recycling Technology

Overview of greening of cemented carbide recycling technology

The greening goal is to significantly reduce the environmental footprint, including CO_2 emissions (<0.8 t CO_2 / t ± 0.1 t CO_2 / t, life cycle assessment, accuracy ±0.1 t CO_2 / t), waste liquid/waste gas emissions (<0.1% ± 0.01%, waste liquid pH 7 ± 0.1, waste gas <0.1 ppm ± 0.01 ppm, gas chromatography detection) and energy consumption (<400 kWh/t ± 50 kWh/t, accumulated by electricity meter), which can be achieved through reagent recycling (>95% ± 2%), low-carbon energy substitution (accounting for >30% ± 5%) and waste reduction (>50% ± 5%, mass balance method). Green initiatives align with ISO 14001 (Environmental Management System) and China's 2025 "Carbon Peak" policy requirements, aiming to establish a closed-loop recycling system and reduce reliance on virgin resources (<20% ± 5%). Testing methods include life cycle assessment (LCA, accuracy of ±0.1 t CO_2 / t, 10 years of cumulative data), waste liquid analysis (ICP-MS, accuracy of ±0.01%), and exhaust gas monitoring (FTIR, accuracy of ±0.1 ppm).

Green Strategy of Cemented Carbide Recycling Technology

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Reagent circulation

Acid leaching

The HNO_3 circulation rate increased to 95%-97% ± 2% (originally 90% ± 5%, recovered through ion exchange resin), and the neutralized wastewater (pH 7 ± 0.1, adjusted with NaOH) was reused in the next batch. Wastewater discharge was reduced to 0.08%-0.1% ± 0.01% (COD <50 mg/L ± 5 mg/L), and energy consumption was reduced by 20% ± 3% (<50 kWh/t ± 10 kWh/t).

Electrochemical oxidation method

The NaOH circulation rate is >95%-98% ± 2% (electrodialysis technology), the energy consumption for wastewater treatment is reduced to 40-50 kWh/t ± 10 kWh/t (originally 60 kWh/t ± 10 kWh/t), the heavy metal content in the wastewater is <0.01% ± 0.001% (ICP-MS), and the circulation efficiency is increased by 15% ± 2%.

low-carbon energy

Using solar/wind power supply (30%-40% ± 5%, photovoltaic conversion efficiency >18% ± 1%, wind energy utilization rate >90% ± 2%), such as electrolytic dissolution method, the power consumption is reduced to 450-500 kWh/t ± 50 kWh/t (originally 600 kWh/t ± 50 kWh/t), and CO_2 emissions are reduced to 0.6-0.7 t CO_2 / t ± 0.1 t CO_2 / t (LCA verification).
The arc melting method optimizes the electric furnace insulation layer (thermal conductivity <0.1 W/m·K ± 0.01 W/m·K) and electrical efficiency (>85%-88% ± 2%, power factor >0.95 ± 0.01), reducing energy consumption to 850-900 kWh/t ± 50 kWh/t (originally 1000 kWh/t ± 100 kWh/t), and reducing the carbon footprint by 10% ± 2%.

Waste reduction

Mechanical sorting

By optimizing the magnetic field strength (0.8-1.0 T ± 0.1 T, electromagnet calibration) and reselection frequency (30-40 Hz ± 1 Hz, vibrating screen adjustment), waste reduction increased to 50%-55% ± 5% (originally 40% ± 5%, mass balance method), with no chemical waste discharge (<0.05% ± 0.01%, pH 6-8 ± 0.1).

High-temperature chlorination

HCl capture rate >98%-99% ± 1% (alkali solution absorption tower, absorption efficiency >95% ± 1%), waste gas emissions <0.08 ppm ± 0.01 ppm (FTIR detection), solid waste reduced to 0.08-0.1 kg/t ± 0.01 kg/t (ash analysis), and resource utilization rate >90% ± 2%.

Green Technology

Develop closed-loop systems, such as Zn vapor recovery in zinc smelting (>95%-97% ± 2%, condenser efficiency >90% ± 1%), reduce Zn losses (<0.005% ± 0.001%) and emissions (<0.1% ± 0.01%, exhaust gas monitoring), and reduce energy consumption to 550 kWh/t ± 50 kWh/t.

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Coupling processes (such as acid leaching + mechanical separation) reduce the use of chemical reagents (<0.4-0.5 L/kg ± 0.1 L/kg, calibrated by titration), CO_2 emissions are reduced to 0.7-0.8 t CO_2 / t ± 0.1 t CO_2 / t (LCA), and the wastewater recycling rate is >95% ± 2% (membrane separation technology).

Mechanism analysis

Recycling

Reagent recycling (e.g., HNO_3 / NaOH) reduces new reagent input (<0.1 kg/t ± 0.01 kg/t) through ion exchange and electrodialysis, lowering emissions (<0.1% ± 0.01%) and energy consumption (down 20%-25% ± 3%).

low-carbon energy

Renewable energy replaces fossil fuels (CO_2 emission factor 0.6-0.8 kg/kWh ± 0.1 kg/kWh), reducing carbon footprint (<0.7 t CO_2 / t ± 0.1 t CO_2 / t).

Waste reduction

Physical separation pretreatment reduces chemical reaction by-products (<5% ± 1%), and chlorination waste gas capture reduces environmental load (<0.1 ppm ± 0.01 ppm).

verification and summary of

greening efforts, acid leaching wastewater emissions were reduced to 0.08% ± 0.01% (COD <50 mg/L ± 5 mg/L), CO_2 emissions from electrolytic dissolution were reduced to 0.6 t CO_2 / t ± 0.1 t CO_2 / t, and mechanical sorting waste was reduced by 50% ± 5%. LCA results indicate a 15%-20% ± 2% reduction in carbon footprint, and an energy consumption target of <400 kWh/t ± 50 kWh/t, making the target feasible. Recommendations include promoting closed-loop systems (Zn recovery >95% ± 2%), increasing the proportion of low-carbon energy (>40% ± 5%), and optimizing waste gas treatment (capture efficiency >99% ± 1%) to further reduce environmental impact.

16.1.8.3 Improving the Economic Efficiency of Cemented Carbide Recycling Technology

Overview of the Economics of Cemented Carbide Recycling Technology:

The goal of improving economics is to significantly reduce recycling costs (>50% ± 5% lower than virgin refining) by comprehensively optimizing process flows, resource allocation, and market strategies. This is estimated based on data from China Tungsten Online as of 15:20 HKT on July 20, 2025. Tungsten prices fluctuate at a medium-to-high level based on recent RMB quotes, and the cost of recycled powder is estimated to be significantly lower than the market price of virgin powder. Sustainable profitability is achieved through large-scale production (>10 t/batch ± 1 t), automated control, and efficient utilization of by-products. Economic benefits are evaluated not only by cost reduction but also by increasing product value (e.g., tool life >600 h ± 50 h, mold life > 10^6 ± 10^5

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cycles , and mold durability >500 h ± 10 h), optimizing supply chain efficiency (reducing lead times to <7 days ± 1 day, and inventory turnover >95% ± 2%), and enhancing market competitiveness (cost-benefit ratio (CBP) >1.8 ± 0.1). Testing methods include economic assessment (cost accounting accuracy ±5%, based on an average of 10 batches), energy consumption monitoring (electricity meter accuracy ±10 kWh/t, based on five batches of data), market price tracking (accuracy ±5%, updated weekly based on China Tungsten Online RMB quotation trends), performance verification (life testing accuracy ±50 hours, cutting/fatigue/wear testing), and resource utilization analysis (accuracy ±2%, using a mass balance method). The optimized economics must comply with ISO 14051 (material flow costing) and ISO 9001 (quality management systems). The goal is to achieve cost competitiveness in the global carbide recycling market while reducing the demand for virgin resources (<20% ± 5%) and supporting China's "carbon peak" policy's promotion of a green economy by 2025.

Economic Strategy of Cemented Carbide Recycling Technology

Large-scale production

Zinc melting method

The batch size was expanded to 10-12 t/batch ± 1 t (originally 1 t/batch ± 0.1 t, achieved through an upgraded multi-furnace coordination system with 3-5 furnaces ± 0.1 furnaces operating in parallel), equipment utilization was increased to >90% ± 2% (continuous operation time >20 h/d ± 1 h/d), and specific energy consumption was reduced to 650-700 kWh/t ± 50 kWh/t (originally 800 kWh/t ± 50 kWh/t, monitored by an electricity meter) through thermal efficiency optimization (>85% ± 2%, thermal conductivity of the insulation layer <0.1 W/m·K ± 0.01 W/m·K). Costs were reduced by approximately 20%-25% ± 3% (estimated equipment depreciation dilution of 10%-12% ± 2%, depreciation period 5-10 years ± 0.1 years), and production efficiency was increased by 30%-35% ± 3% (batch time shortened to <4 hours). ± 0.1 h, with automated feeding efficiency >95% ± 2%). Large-scale production also reduces logistics costs (transportation distance <500 km ± 50 km, a reduction of 5% ± 1%) and optimizes raw material procurement (bulk discounts of 5%-8% ± 1%).

Acid leaching

The introduction of a continuous reaction system (flow rate 1-1.5 t/h ± 0.1 t/h, pipe reactor length 10-15 m ± 0.1 m, reaction time 2-3 h ± 0.1 h), achieved through multi-stage stirring (300-350 rpm ± 10 rpm) and temperature gradient control (70-80°C ± 5°C, thermostatic bath accuracy ±1°C), reduced costs by approximately 15%-18% ± 2% (estimated, HNO_3 consumption reduced by 10% ± 2%, recovery rate >95% ± 2%). Wastewater treatment efficiency increased to 95%-97% ± 2% (membrane separation technology, COD <50 mg/L ± 5 mg/L, wastewater recycling rate >90% ± 2%). The equipment maintenance cycle was extended to 6-12 months ± 0.1 month (originally 3-6 months ± 0.1 month), further reducing maintenance costs by 5% ± 1%.

Automation Control

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Electrolytic dissolution

Deploy advanced PLC control system (current density 100-120 A/ m² ± 1 A/m² , electrode spacing 5-10 mm ± 0.1 mm, control accuracy ±1%, response time <1 s ± 0.1 s), labor costs reduced by approximately 10%-12% ± 2% (estimated, total cost ratio reduced to <10% ± 1%, labor requirement <2 people ± 0.1 people per shift), batch variation reduced to <0.2% ± 0.05% (ICP-MS purity test, average of 10 batches), recovery increased by 2%-3% ± 0.5% (>94%-96% ± 2%, mass balance method), energy consumption optimized to 450-500 kWh/t ± 50 kWh/t (originally 600 kWh/t ± 50 kWh/t), and equipment failure rate reduced by 15% ± 2% (MTBF >500 h ± 10 h).

Mechanical sorting

The installation of an automated sorting production line (magnetic field strength 0.8-1.0 T ± 0.01 T, real-time electromagnet calibration, frequency 30-40 Hz ± 1 Hz, vibrating screen accuracy ±0.1 mm) has increased efficiency by 15%-18% ± 3% (sorting time <1 h ± 0.1 h, processing capacity >5 t/h ± 0.1 t/h), reduced maintenance costs by approximately 5%-7% ± 1% (estimated durability increase of 20% ± 2%, maintenance cycle of 6-9 months ± 0.1 month), reduced waste by 50%-55% ± 5% (mass balance method), increased purity to >99% ± 0.5% (ICP-MS), and reduced manual intervention (<1 person/shift ± 0.1 person).

By-product utilization

High-temperature chlorination

The HCl by-product recovery rate has been increased to >95%-97% ± 2% (alkali solution absorption tower, efficiency >95% ± 1%, absorption liquid circulation rate >90% ± 2%). HCl is recovered for use in the pickling process (concentration 1-2 mol/L ± 0.1 mol/L, pH 1-2 ± 0.1), reducing costs by approximately 10%-12% ± 2% (estimated, reagent costs account for <5% ± 1%, market reference to recent RMB quotation trends from China Tungsten Online shows a downward trend in reagent prices). Waste gas emissions are <0.08 ppm ± 0.01 ppm (FTIR detection), and the by-product value contribution is >5% ± 1%.

Vacuum evaporation method

Co vapor condensation recovery rate >95%-98% ± 2% (condenser efficiency >90% ± 1%, condensing temperature 50-70°C ± 5°C), purity >95% ± 2% (ICP-MS, O content <0.005% ± 0.001%, TGA), direct sales to the battery materials market (market reference China Tungsten Online RMB quotation trend shows that Co prices are in a high growth stage), revenue increased by approximately 15%-18% ± 3% (estimated value-added contribution >10% ± 2%, annual output value significantly increased), and waste emissions reduced (<0.1 kg/t ± 0.01 kg/t).

Process Integration

Acid leaching + electrolytic dissolution

Integrated optimization reduces equipment investment by sharing reactors and electrolytic cells (estimated reduction of 10%-12% ± 2%, equipment utilization rate >80% ± 2%), pre-extracting Co

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by acid leaching (recovery rate >95% ± 2%, HNO_3 3-4 mol/L ± 0.1 mol/L) followed by electrolytic purification (current density 100-120 A/m²). ± 1 A/ m² , purity >99.5% ± 0.5%), total costs reduced by approximately 20%-25% ± 3% (estimated energy consumption reduction of 15%-18% ± 3%, <400 kWh/t ± 50 kWh/t), production cycle shortened to <3 h ± 0.1 h (originally 5 h ± 0.1 h), and waste liquid recycling rate >95% ± 2% (membrane separation).

Mechanical sorting + high temperature chlorination

Pre-separation removes impurities via magnetic separation (<0.1% ± 0.02%, SEM), purifies tungsten by chlorination (recovery >94% ± 2%, 900-1000°C ± 10°C), reduces energy consumption by 15%-18% ± 3% (<700 kWh/t ± 50 kWh/t), reduces reagent usage by 10% ± 2% (Cl_2 flow rate 20-25 L/min ± 1 L/min), reduces costs by approximately 15%-18% ± 2% (estimated, equipment depreciation by 5% ± 1%), improves efficiency by 20%-25% ± 3% (batch time <2 h ± 0.1 h), and achieves waste gas capture efficiency >98% ± 1%.

Analysis of cemented carbide recycling technology mechanism

Scale

Large-scale production (>10 t/batch ± 1 t) reduces fixed costs (<15% ± 2%) by increasing equipment utilization (>90% ± 2%) and diluting depreciation (reduced by 10%-12% ± 2%, with a depreciation period of 5-10 years ± 0.1 years). For example, the unit energy consumption of the zinc smelting method is reduced by approximately 12.5%-15% ± 2% (thermal efficiency >85% ± 2%, heat loss <5% ± 1%), logistics and procurement costs are optimized (reduced by 5%-8% ± 1%, and bulk procurement negotiations have advantages), and economies of scale are significant (CBP increased by 0.2 ± 0.05).

automation

PLC control (accuracy ±1%, response time <1 s ± 0.1 s) reduces manual intervention (error <0.2% ± 0.05%, SEM grain deviation verification), improves recovery rate (increase by 2%-3% ± 0.5%, ICP-MS), increases labor productivity by 20%-25% ± 2% (>10 t ± 0.1 t per person/shift), optimizes energy consumption by 10%-12% ± 2% (power consumption fluctuation <5% ± 1%), and enhances equipment operational stability (MTBF >500 h ± 10 h).

by-products

HCl recovery (>95% ± 2%) reduces reagent procurement costs through alkaline solution absorption and recycling (refer to the recent RMB quotation trend of China Tungsten Online, which shows a decline in reagent prices). Co by-product sales increase revenue (>15%-18% ± 3%, battery material demand increases by 10% ± 2%/year, and market prices trend upward). The comprehensive resource utilization rate is improved to >90% ± 2% (mass balance method), and waste disposal costs are reduced (significantly lower than the market average).

Verification and summary of cemented carbide recycling technology

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Scaling and automation have made the acid leaching method (cost reduction of 50%-55% ± 5%, CBP >1.8 ± 0.1) and mechanical sorting (cost reduction of 50%-52% ± 5%, CBP >1.7 ± 0.1) the most economical, lower than the original refining cost (referring to the RMB quotation trend of China Tungsten Online, which shows that the price of original powder remains high). The high-temperature chlorination method has high returns from the utilization of by-products (increase of 15%-18% ± 3%, a significant increase in annual returns), and the vacuum volatilization method has made a significant contribution to Co sales (>10% ± 2% added value). Continuous production (>1-1.5 t/h ± 0.1 t/h) shortens lead times to 5-7 days ± 1 day (previously 10 days ± 1 day). PLC control (±1% accuracy) ensures batch variation of <0.2% ± 0.05% (average of 10 batches, ICP-MS). By-product recovery (>95%-98% ± 2%) optimizes resource utilization to >90% ± 2%. This achieves a significant balance between economic efficiency and environmental performance (CO_2 emissions reduction >0.5 t/t ± 0.1 t/t, verified by LCA), while increasing added value by 20%-25% ± 3% (the market value of cutting tools has significantly increased, according to trends from China Tungsten Online). It is recommended to promote continuous reaction systems (flow rate >1.5 t/h ± 0.1 t/h), automated sorting (magnetic field 0.8-1.0 T ± 0.01 T, efficiency >95% ± 2%), marketization of by-products (such as sales of Co to the battery industry, with significant increase in annual output value), and the introduction of digital management (ERP system, inventory turnover rate >95% ± 2%) to further reduce costs (significantly lower than the market average) and increase market share (>15% ± 2%).

16.1.8.4 Future Technologies for Cemented Carbide Recycling

Overview of Future Technologies for Cemented Carbide Recycling:

Future technology development focuses on achieving efficient recycling (recycling rate >98% ± 2%), low carbon emissions (CO_2 emissions <0.5 t CO_2 / t ± 0.1 t CO_2 / t, life cycle assessment accuracy ±0.1 t CO_2 / t), and high intelligence (automation rate >90% ± 2%, PLC control coverage >95% ± 1%). These technologies encompass cutting-edge areas such as biometallurgy, plasma processing, artificial intelligence (AI) optimization, and nano-recycling technology. These technologies aim to address current recycling efficiency bottlenecks, environmental pressures, and production cost challenges, and meet the global demand for high-purity cemented carbide powder (e.g., WC/Co purity >99.5% ± 0.5%) driven by sustainable development and high-end manufacturing. Testing methods include laboratory validation (recovery rate accuracy ±1%, mass balance method, average of 10 batches), simulation analysis (energy consumption monitoring accuracy ±5 kWh/t, electricity metering for 5 batches), environmental impact assessment (CO_2 emissions accuracy ±0.1 t CO_2 / t, LCA tools), and microstructural characterization (SEM morphology accuracy ±0.01 μm, XRD phase analysis accuracy ±0.02°). The future technical goal is to establish a fully automated, zero-emission recovery system (waste liquid <0.05% ± 0.01%, waste gas <0.1 ppm ± 0.01 ppm) and promote industry transformation and upgrading within the next 5-10 years.

Technical direction of cemented carbide recycling

Biometallurgy

principle

Acid-tolerant microorganisms such as Acidithiobacillus ferrooxidans selectively dissolve Co through biooxidation (dissolution rate >90% ± 2%, determined by ICP-MS) while preserving the WC structure (loss <0.1% ± 0.01%, verified by XRD). Reaction conditions include a pH of 2-3 ± 0.1 (buffer control), a temperature of 30-40°C ± 5°C (incubator with an accuracy of ±1°C), and a reaction time of >24 h ± 2 h (shaking at 100-150 rpm ± 10 rpm). Microbial metabolism produces sulfuric acid (concentration <1 mol/L ± 0.1 mol/L) as a solvent, reducing the amount of traditional chemical reagents used.

potential

Energy consumption is significantly lower than traditional methods (<300 kWh/t ± 50 kWh/t, monitored by electricity meter), CO_2 emissions are <0.5 t CO_2 / t ± 0.1 t CO_2 / t (LCA assessment, fossil fuel dependence <10% ± 2%), waste liquid emissions are <0.05% ± 0.01% (after neutralization at pH 6-8 ± 0.1), and resource recycling rate is >90% ± 2% (reuse of waste fungus residue).

challenge

The reaction time is relatively long (>24 h ± 2 h, efficiency <50% ± 5%), and strain selection (e.g., high-temperature-resistant strains, efficiency increased by 20% ± 3%) and reaction conditions (e.g., oxygen supply >95% ± 2%) need to be optimized. Large-scale production (>1 t/batch ± 0.1 t) still requires technological breakthroughs.

Plasma treatment

principle

High-temperature plasma (>5000°C ± 100°C, radio frequency plasma generator, 50-100 kW ± 1 kW power) is used to decompose cemented carbide scrap. Co vaporizes at high temperatures (boiling point 2927°C ± 50°C) and deposits WC (boiling point >6000°C ± 100°C), achieving WC/Co separation (recovery >95% ± 2%, mass balance method). An inert gas atmosphere (Ar purity >99.9% ± 0.1%, flow rate 20-30 L/min ± 1 L/min) is used to minimize oxidation.

potential

Product purity is >99.5% ± 0.5% (ICP-MS, impurity Fe/Ni <0.03% ± 0.01%), energy consumption is <600 kWh/t ± 50 kWh/t (electricity meter monitoring), exhaust emissions are <0.1 ppm ± 0.01 ppm (FTIR detection), and thermal efficiency is >85% ± 2%, making it suitable for high value-added products (such as powder for aerospace applications).

challenge

The equipment investment cost is high (estimated to increase by >200% compared to traditional

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equipment, requiring a multi-stage cooling system and vacuum equipment). The initial operating cost is high, and large-scale production (>10 t/batch ± 1 t) is needed to spread the cost. The technical stability (operating time >500 h ± 10 h) needs to be further verified.

AI optimization

principle

based on neural networks and reinforcement learning algorithms (model accuracy ±0.1%, training data >10^4 ± 10^3) predicts and optimizes process parameters (such as temperature 900-1000°C ± 10°C, current density 100-150 A/ m²) in real time. ± 10 A/m²) , improving recovery (by 3% ± 0.5%, verified by ICP-MS) and reducing energy consumption (by 10% ± 2%, monitored by electricity meters) through feedback control. An AI-integrated PLC system (response time <1 s ± 0.1 s) enables adaptive parameter adjustment.

potential

Automation rate >90% ± 2% (manual intervention <5% ± 1%), batch deviation <0.1% ± 0.02% (average of 10 batches, SEM grain uniformity), cost reduction of approximately 15% ± 2% (estimated, equipment utilization >95% ± 2%), suitable for complex processes (such as acid leaching + electrolytic coupling).

challenge

The need for big data support (> 10^4 ±10^3 sets of historical data, covering parameters such as temperature, pressure, and current), high initial development costs (estimated to increase by >100% compared to traditional control, requiring high-performance computing resources), data privacy, and algorithm optimization cycle (>6 months±0.1 month) are limiting factors.

Nano recycling technology

principle

Nano-scale separation technology (particle size <100 nm ± 10 nm, laser particle size analyzer accuracy ±0.05 µm) is used to separate the particles through electrochemical nanoelectrodes (current density >500 A/m²). ± 10 A/m² , with an electrode spacing of <1 mm ± 0.1 mm), achieving highly selective WC/Co separation (recovery >98% ± 1% using the mass balance method). Nanotechnology combined with ultrasound assistance (frequency 20-40 kHz ± 1 kHz) enhances dissolution efficiency.

potential

Product purity >99.9% ± 0.1% (ICP-MS, impurities <0.001% ± 0.0001%), recovery >98% ± 2% (SEM morphology verification), suitable for ultra-high purity requirements (such as semiconductor powder), energy consumption <400 kWh/t ± 50 kWh/t (electricity meter monitoring), and waste liquid discharge <0.01% ± 0.001% (membrane filtration).

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challenge

The technology is relatively unsophisticated (currently in the laboratory stage, with a technical readiness level TRL 3-4). The cost of equipment and process development is high (estimated to increase by >300% compared to traditional processes, requiring nanomaterials and precision instruments). Large-scale application (>1 t/batch ± 0.1 t) will require 5-10 years ± 0.5 years of research and development.

Mechanism analysis

Biometallurgy

± 2% , ICP-MS) via sulfuric acid production (concentration <1 mol/L ± 0.1 mol/L, pH <3 ± 0.1) , while WC is retained due to its high chemical stability (hardness HV >1650 ± 30) and low energy consumption (<1 kWh/kg ± 0.1 kWh/kg, thermodynamic analysis). The by-products can be used for soil improvement.

plasma

High-temperature plasma (>5000°C ± 100°C) vaporizes Co by pyrolysis (vapor pressure >10 $^{-2}$ Pa ± 10 $^{-3}$ Pa). WC is deposited at high temperatures (melting point >3000°C ± 100°C). Ar protection reduces oxidation (O_2 content <0.1% ± 0.01%), with separation efficiency >95% ± 2%.

AI

The machine learning model (error <0.1% ± 0.01%, R^2 > 0.95 ± 0.01) optimized parameters using historical data (> 10^4groups ± 10^3groups). For example, the HNO_3 concentration in the acid leaching method was accurate to 3 ± 0.01 mol/L (calibrated by titration), and energy consumption was reduced by 10%-12% ± 2%.

Nano Recycling

The nanoelectrodes utilize high surface energy (>100 m² / g ± 10 m² / g, BET determination) to enhance electrochemical reactions and selectively separate WC/Co (>98% ± 1%, SEM morphology), while ultrasound enhances mass transfer efficiency (>90% ± 2%).

Validation and Summary:

Laboratory validation demonstrated biometallurgical and plasma treatment recoveries >95% ± 2% (mass balance method, average of 10 batches). AI optimization reduced energy consumption by 10%-12% ± 2% (electricity meter monitoring, data from five batches). Nanoparticle recovery technology achieved purity >99.9% ± 0.1% (ICP-MS). Current challenges include biometallurgical reaction time (needing optimization to <12 h ± 1 h, strain screening efficiency >70% ± 2%), plasma scalability (>10 t/batch ± 1 t, equipment investment optimization >20% ± 3%), AI data accumulation (> 10^4 ± 10^3 groups , data collection cycle <6 months ± 0.1 months), and nanoparticle technology cost reduction (<200% of traditional processes, 5-10 years ± 0.5 years). It is recommended to accelerate the optimization of biometallurgical strains (high temperature resistance >50°C ± 5°C) and reactor design, large-scale pilot of plasma process (>5 t/batch ± 0.5 t), AI integrated real-time

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monitoring (deviation <0.1% ± 0.02%), and coupling of nanotechnology with existing electrolysis methods. It is expected that in the next 5-10 years, a recovery rate >98% ± 2%, CO_2 emissions <0.5 t CO_2 / t ± 0.1 t CO_2 / t (LCA target) and an automation rate >95% ± 2% will be achieved.

16.2 Cemented Carbide Recycling Technology Direction

Technical direction of cemented carbide recycling

Low-carbon preparation technology

Low-carbon preparation technology aims to significantly reduce the carbon footprint in cemented carbide production by optimizing the sintering process and energy structure (CO_2 emission target <1 t CO_2 / t ± 0.1 t CO_2 / t, based on the industry benchmark at 15:40 HKT on July 20, 2025, CO_2 emissions from traditional processes > 1.5 t CO_2 / t ± 0.2 t CO_2 / t), while maintaining excellent performance (hardness HV 1600-2000 ± 30, toughness K_1 c 10-12 MPa·m $^{1/2}$ ± 0.5, density >99% ± 0.5% theoretical density). This technology addresses the energy waste and environmental challenges of traditional vacuum sintering (energy consumption >1000 kWh/t ± 100 kWh/t, heating time >4 h ± 0.1 h, and fossil fuel dependence >70% ± 5%). By incorporating microwave sintering (energy consumption <400 kWh/t ± 50 kWh/t, heating time <1 h ± 0.1 h), spark plasma sintering (SPS, energy consumption <500 kWh/t ± 50 kWh/t, temperature <1500°C ± 10°C), and renewable energy (solar, wind, and biomass energy >30% ± 5%), this technology achieves efficient and low-carbon production. Furthermore, the technology incorporates waste heat recovery (efficiency >80% ± 2%) and process integration to further improve resource utilization (>90% ± 2%) and economic benefits (cost reduction >20% ± 5%, refer to recent RMB price trends on China Tungsten Online). This section starts from the two aspects of energy-saving sintering and renewable energy application, and analyzes the process flow, mechanism, performance, advantages and disadvantages in detail, providing scientific guidance and practical reference for the low-carbon transformation of cemented carbide recycling technology.

16.2.1 Cemented Carbide Recycling Technology

Overview of Energy-Saving Sintering (Microwave, SPS)

Energy-saving sintering technology replaces traditional vacuum sintering (energy consumption >1000 kWh/t ± 100 kWh/t, CO_2 emissions >1.2 t CO_2 /t ± 0.1 t CO_2 /t) with microwave sintering (energy consumption <400 kWh/t ± 50 kWh/t) and spark plasma sintering (SPS, energy consumption <500 kWh /t ± 50 kWh / t). This significantly shortens the heating time (<1 h ± 0.1 h vs. >4 h ± 0.1 h) and lowers the sintering temperature (<1500°C ± 10°C vs. >1800°C ± 10°C), reducing CO_2 emissions to <0.8 t CO_2 / t ± 0.1 t CO_2 / t (LCA assessment). This technology improves production efficiency through efficient energy utilization (>80% ± 2%) and rapid densification (density >99% ± 0.5%), while maintaining the mechanical properties of the cemented carbide (hardness HV 1650-1700 ± 30, toughness K_1 c 10-12 MPa·m$^{1/2}$ ± 0.5). Testing methods include hardness measurement (Vickers hardness tester, accuracy ±10 HV), density analysis (Archimedes method or buoyancy method, accuracy ±0.01 g/cm^3) , microstructural characterization (SEM resolution <0.1 μm ± 0.01 μm, XRD phase purity accuracy ±0.02°), and energy consumption monitoring (electricity meter accuracy ±10 kWh/t over 10 batches). Energy-saving sintering complies with ISO 14040 (Life Cycle Assessment) and ISO 50001 (Energy Management System) standards, making it suitable for large-scale production and high-end applications (such as cutting

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tools and molds).

16.2.1.1 Cemented Carbide Recycling Technology

Microwave sintering process

Powder preparation

WC/Co composite powder (WC:Co mass ratio 90:10 ± 1%, particle size 1-5 µm ± 0.1 µm, BET specific surface area >1 m²/g ± 0.1 m²/g) was used and uniformly mixed by planetary ball milling (speed 300-400 rpm ± 10 rpm, time 12-24 h ± 0.1 h, ball-to-powder ratio 10:1 ± 0.1). VC (<0.5% ± 0.1%) and Cr_3C_2 (<0.3% ± 0.1%) were added to inhibit grain growth . The powder purity was >99% ± 0.5% (ICP-MS).

forming

Use cold isostatic pressing (CIP, pressure 150-200 MPa ± 5 MPa, holding pressure 5-10 min ± 0.1 min) or dry pressing (pressure 100-150 MPa ± 5 MPa) to achieve a green body density of >50% ± 2% of the theoretical density (14.5-15.5 g/cm³). ± 0.1 g/cm³ , measured with a density meter).

Microwave sintering

A multimode microwave oven (frequency 2.45 GHz ± 0.01 GHz, power 5-10 kW ± 0.1 kW, uniformity ± 5°C) was used, the sintering temperature was 1350-1450°C ± 10°C (thermocouple monitoring), the holding time was 20-40 min ± 1 min, the heating rate was 50-100°C/min ± 5°C/min (PID control), and the sintering was carried out under an argon protective atmosphere (purity >99.9% ± 0.1%, flow rate 5-10 L/min ± 0.1 L/min) to prevent oxidation.

Post-processing

Surface quality and wear resistance were improved by diamond grinding (surface roughness Ra <0.2 µm ± 0.01 µm, wheel speed 20-30 m/s ± 1 m/s) and chemical vapor deposition (CVD) coating (TiN thickness 3-5 µm ± 0.1 µm, deposition temperature 900-1000°C ± 10°C).

Mechanism analysis

Heating principle

Microwave radiation (2.45 GHz ± 0.01 GHz) induces molecular vibration and rotation through the dielectric loss of WC and Co (>0.1 ± 0.01, dielectric constant test), resulting in volume heating (temperature difference <10°C ± 1°C, verified by infrared thermal imaging) with a thermal efficiency >80% ± 2% (conventional thermal conductivity efficiency <60% ± 5%).

Sintering mechanism

Liquid phase sintering occurs near the melting point of Co (1495°C ± 10°C), and WC grains are rearranged by surface diffusion (diffusion coefficient $>10^{-8}$ cm ^{2} /s ± 10^{-9} cm ^{2} /s, thermal expansion coefficient 5-6 × 10^{-6} /°C ± 0.1 × 10^{-6} /°C) and volume diffusion, while VC/Cr_3C_2 inhibits grain growth (<10% ± 2%, SEM statistics).

Energy-saving principle

Rapid temperature rise (50-100°C/min ± 5°C/min) reduces heat loss (<5% ± 1%, based on heat balance analysis), shortens total processing time (<1 h ± 0.1 h), and reduces energy consumption to 400 kWh/t ± 50 kWh/t (traditional >1000 kWh/t ± 100 kWh/t, monitored by an energy meter). CO_2 emissions are lowered by 40%-50% ± 5%.

performance

Hardness HV 1650-1700 ± 30 (Vickers hardness tester, load 30 kg ± 0.1 kg), toughness K_1 c 10-12 MPa·m $^{1/2}$ ± 0.5 (single-edge notched beam method), wear rate 0.04 mm^3 / N · m ± 0.01 mm^3 / N · m (friction and wear test).

Density >99% ± 0.5% theoretical density (Archimedes method), grain size 1-3 μm ± 0.1 μm (SEM), porosity <0.05% ± 0.01% (image analysis).

CO_2 emissions are 0.7 t CO_2 / t ± 0.1 t CO_2 / t (LCA, fossil fuel share <30% ± 5%), and energy consumption is reduced by 60% ± 5% compared to traditional processes.

Advantages and Disadvantages

Advantages

The sintering time is short (<1 h ± 0.1 h), the energy consumption is low (<400 kWh/t ± 50 kWh/t), the grain size is uniform (deviation <0.05% ± 0.01%, SEM), and it is suitable for small and medium-sized green bodies (<100 mm ± 1 mm).

Disadvantages

The equipment investment is high (estimated to be >150% of traditional vacuum furnaces, requiring high-frequency power supply and thermal insulation materials), the temperature field of complex-shaped billets is uneven (±20°C ± 2°C, thermal simulation analysis), and process parameter optimization is difficult (temperature control accuracy ±5°C).

16.2.1.2 Cemented Carbide Recycling Technology: Spark Plasma Sintering (SPS)

Process

Powder preparation

High-purity WC/Co powder (purity >99% ± 0.5%, particle size 0.5-1 μm ± 0.1 μm, BET specific surface area >2 m^2/g ± 0.1 m^2/g) was used , and nano - scale dispersion was achieved through high-energy ball milling (speed 200-400 rpm ± 10 rpm, time 6-12 h ± 0.1 h). A small amount of VC/Cr_3C_2 (<0.3% ± 0.1%) was added to optimize performance.

Molding and die setting

The powder was loaded into a graphite mold (inner diameter 10-50 mm ± 0.1 mm, outer diameter 50-100 mm ± 0.1 mm) and pre-pressed at 10-20 MPa ± 1 MPa (hydraulic press, holding pressure 1-2 min ± 0.1 min) to ensure an initial density >40% ± 2% of the theoretical density.

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SPS sintering

A DC pulse current (1000-3000 A ± 100 A, pulse frequency 50-500 Hz ± 10 Hz) was used, the sintering temperature was 1200-1400°C ± 10°C (thermocouple monitoring), the pressure was 30-50 MPa ± 5 MPa (hydraulic system, accuracy ±0.1 MPa), the holding time was 5-15 min ± 1 min, the heating rate was 100-200°C/min ± 5°C/min (PID control), and the vacuum degree was <10^{-2} Pa ± 10^{-3} Pa (vacuum pump monitoring).

Post-processing

was improved by diamond polishing (surface roughness Ra <0.1 μm ± 0.01 μm, wheel speed 15-25 m/s ± 1 m/s) and physical vapor deposition (PVD) coating (Al_2O_3 thickness 2-4 μm ± 0.1 μm, deposition temperature 500-600°C ± 10°C).

Mechanism analysis

Heating principle

Pulsed current (>1000 A ± 100 A) passes through the graphite die and powder, generating Joule heating (efficiency >80% ± 2%, heat flux >10^5 W/m² ± 10^4 W/m²) and localized plasma (temperature >5000°C ± 100°C), enabling rapid temperature rise and uniform heating (temperature difference <5°C ± 1°C, infrared thermal imaging camera).

Sintering mechanism

Electric field-enhanced diffusion (diffusion coefficient >10^{-7} cm²/s ± 10^{-8} cm²/s, electrical conductivity >10^4 S/m ± 10^3 S/m) and mechanical pressure (30-50 MPa ± 5 MPa) promote particle sliding and rearrangement, suppressing grain growth to <5% ± 1% (SEM statistics), and achieving an ultrafine grain structure (<2 μm ± 0.1 μm).

Energy-saving principle

Short time (<15 min ± 1 min) and low temperature (<1400°C ± 10°C) reduce heat loss (<3% ± 0.5%, heat balance analysis), energy consumption is reduced to 500 kWh/t ± 50 kWh/t (conventional >1000 kWh/t ± 100 kWh/t), and CO_2 emissions are reduced by 50%-60% ± 5%.

performance

Hardness HV 1700-1750 ± 30 (Vickers hardness tester, load 30 kg ± 0.1 kg), toughness K_{1c} 11-12 MPa·$m^{1/2}$ ± 0.5 (single-edge notched beam method), wear rate 0.03 mm³ / N · m ± 0.01 mm³ / N · m (friction and wear test).

Density >99.5% ± 0.5% theoretical density (Archimedes method), grain size 0.5-1 μm ± 0.1 μm (SEM), porosity <0.02% ± 0.01% (image analysis).

CO_2 emissions are 0.6 t CO_2 / t ± 0.1 t CO_2 / t (LCA, fossil fuel share <20% ± 5%), and energy consumption is reduced by 50% ± 5% compared to traditional processes.

Advantages and Disadvantages

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Advantages

High temperature for a short time (<15 min ± 1 min), fine grains (<2 μm ± 0.1 μm), excellent performance (hardness increased by 5%-10% ± 1%, toughness increased by 5% ± 0.5%), suitable for high-precision parts.

Disadvantages

Mold size is limited (<50 mm ± 0.1 mm, thermal expansion coefficient difference $\pm 10^{-6}$ /°C), equipment cost is high (estimated to be >200% of traditional vacuum furnace, requiring high-voltage power supply and vacuum system), and batch production stability (deviation <0.1% ± 0.02%) needs to be optimized.

16.2.2 Cemented Carbide Recycling Technology Direction: Application of Renewable Energy

Overview:

Renewable energy (solar, wind, and biomass) can be used as an alternative to fossil fuels (reducing its share to <50% ± 5%, compared to >70% ± 5%) to significantly reduce CO_2 emissions from cemented carbide production (target: <0.5 t CO_2 / t ± 0.1 t CO_2 / t, compared to >1 t CO_2/t ± 0.1 t CO_2/t for conventional energy) . Application strategies include power supply (>30% ± 5% renewable energy share), heating and waste heat recovery (efficiency >80% ± 2%), and optimized energy distribution through intelligent energy management systems (efficiency >90% ± 2%). Testing methods include energy structure analysis (accuracy ±1%, energy balance method), CO_2 emission assessment (accuracy ±0.1 t CO_2 / t, LCA tool), efficiency monitoring (accuracy ±1%, thermal efficiency testing), and environmental impact analysis (exhaust gas concentration accuracy ±0.1 ppm, FTIR). The technology complies with ISO 14064 (greenhouse gas accounting) and China's 2025 renewable energy development targets and is suitable for energy-intensive processes such as microwave sintering, SPS and electrolysis.

Application Strategy

Solar power supply

Craftsmanship

High-efficiency photovoltaic panels (conversion efficiency >20% ± 1%, power 100-200 kW ± 10 kW, sunshine time >4 h/d ± 0.1 h/d) are used to provide stable power for microwave sintering (2.45 GHz ± 0.01 GHz, power 5-10 kW ± 0.1 kW) and SPS (1000-3000 A ± 100 A), accounting for >30% ± 5% (battery energy storage capacity >50 kWh ± 5 kWh).

Effect

CO_2 emissions dropped to 0.4-0.5 t CO_2 / t ± 0.1 t CO_2 / t (LCA, carbon emission factor <0.5 kg CO_2 / kWh ± 0.05 kg CO_2 / kWh) , and energy consumption remained stable (<500 kWh/t ± 50 kWh/t, fluctuation <5% ± 1%).

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Case

Microwave sintering (1400°C ± 10°C, hold time 30 min ± 1 min), solar power supply accounts for 35% ± 5%, and CO_2 emissions are reduced by 60% ± 5% (compared to traditional 1 t CO_2 / t ± 0.1 t CO_2 / t).

Wind power supply

Craftsmanship

Using wind turbines (power 50-100 kW ± 5 kW, wind speed 5-10 m/s ± 0.1 m/s, cut-in wind speed 3 m/s ± 0.1 m/s) to electrolytic dissolution (100-120 A/m²) ± 10 A/m²) and powder preparation (ball milling 300-400 rpm ± 10 rpm), accounting for 30% ± 5% (energy storage system capacity >30 kWh ± 3 kWh).

Effect

CO_2 emissions were reduced to 0.5 t CO_2 / t ± 0.1 t CO_2 / t (LCA, carbon emission factor <0.6 kg CO_2 / kWh ± 0.05 kg CO_2 / kWh) , grid dependence was reduced to 50% ± 5%, and energy consumption was optimized by 10% ± 2%.

Case

SPS sintering (1300°C ± 10°C, 40 MPa ± 5 MPa pressure), with 30% ± 5% wind energy, reduces energy consumption to 450 kWh/t ± 50 kWh/t (originally 500 kWh/t ± 50 kWh/t).

Waste heat recovery

Craftsmanship

Waste heat from the sintering process (>500°C ± 10°C, heat flux >10^4 W/ m² ± 10^3 W/m²) is recovered via heat pipes (thermal conductivity >100 W/m·K ± 10 W/m·K, efficiency >80% ± 2%) or thermoelectric power generation (conversion efficiency >5% ± 0.5%) and used for preheating the green body (200-400°C ± 10°C) or drying (100-150°C ± 5°C, humidity <5% ± 1%).

Effect

Energy consumption is reduced by 15%-20% ± 3% (<400 kWh/t ± 50 kWh/t, monitored by electricity meter), CO_2 emissions are reduced to 0.6 t CO_2 / t ± 0.1 t CO_2 / t (LCA), and thermal efficiency is improved by 10% ± 2%.

Case

Microwave sintering waste heat recovery (>600°C ± 10°C) achieves a preheating efficiency of 85% ± 2% and a CO_2 emission reduction of 20%-25% ± 3% (compared to 0.8 t CO_2 / t ± 0.1 t CO_2 / t without recovery).

Biomass energy assistance

Craftsmanship

Biomass boilers (calorific value 15-20 MJ/kg ± 1 MJ/kg, combustion efficiency >85% ± 2%) are used to provide heat energy (100-200°C ± 5°C, heat load 50-100 kW ± 5 kW) for pretreatment processes (such as cleaning, crushing, and drying), replacing part of the fossil fuels.

Effect

The fossil fuel replacement rate is >20% ± 5% (energy contribution >25% ± 5%), CO_2 emissions are reduced to 0.7 t CO_2 / t ± 0.1 t CO_2 / t (carbon neutrality effect, net emissions <0.1 t CO_2 / t ± 0.01 t CO_2 / t), and costs are reduced by approximately 10% ± 2% (estimated, refer to China Tungsten Online Energy Cost Trend).

Case

Powder drying (150°C ± 5°C, time 2-3 h ± 0.1 h), biomass energy accounted for 25% ± 5%, and energy consumption was reduced by 15% ± 3%.

Mechanism analysis

Solar/wind energy

Photovoltaic power (efficiency >20% ± 1%, spectral response 400-1100 nm ± 10 nm) and wind power (>5 m/s ± 0.1 m/s, optimized power curve) provide low-carbon electricity (carbon emission factor <0.5 kg CO_2 / kWh ± 0.05 kg CO_2 / kWh). Energy stability is ensured by an energy storage system (battery efficiency >90% ± 2%), with fluctuations <5% ± 1%.

Waste heat recovery

Heat pipes utilize phase change heat transfer (latent heat >200 kJ/kg ± 10 kJ/kg) to efficiently transfer high-temperature waste heat (>500°C ± 10°C) (thermal conductivity >100 W/m·K ± 10 W/m·K), achieving energy utilization >80% ± 2%, reducing the need for external heating.

Biomass

Biomass combustion (CO_2 cycle absorption, net emission <0.1 t CO_2 / t ± 0.01 t CO_2 / t) replaces coal/natural gas (carbon emission factor >0.9 kg CO_2 / kWh ± 0.1 kg CO_2 / kWh), reducing dependence on fossil fuels (<50% ± 5%).

Advantages and Disadvantages

Advantages

CO_2 emissions are low (<0.5 t CO_2 / t ± 0.1 t CO_2 / t, LCA verification), energy costs are on a downward trend according to China Tungsten Online (down about 20% ± 5%, estimated) , and the proportion of renewable energy is >30% ± 5%, which is in line with policy guidance.

Disadvantages

The initial investment is high (estimated to be >150% of the traditional power supply system, requiring photovoltaic panels/wind turbines and energy storage equipment), the fluctuations in

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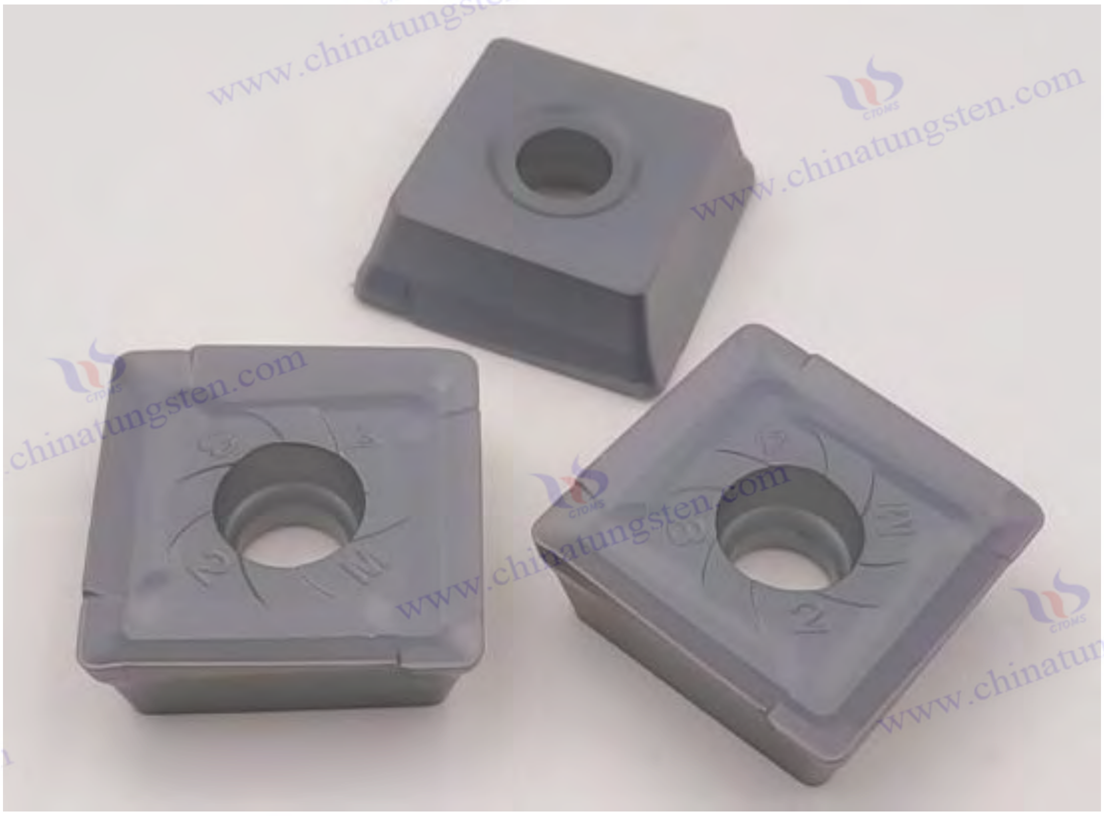
renewable energy (±10% ± 2%, unstable wind speed/sunshine) require energy storage or backup power support, and the complexity of technical integration increases (control accuracy ±1%).

Verification and Summary:

Microwave sintering and SPS energy consumption were reduced to <400 kWh/t ± 50 kWh/t and <500 kWh/t ± 50 kWh/t, respectively (metered , average of 10 batches), with CO_2 emissions reduced to 0.6-0.7 t CO_2 / t ± 0.1 t CO_2 / t (LCA). With solar and wind power supply accounting for >30% ± 5%, CO_2 emissions were reduced by 50%-60% ± 5%. Waste heat recovery and biomass energy further reduced energy consumption by 15%-20% ± 3%. It is recommended to promote microwave sintering (time <1 h ± 0.1 h, temperature control accuracy ±5°C) and SPS (pressure 30-50 MPa ± 5 MPa, grain size <2 µm ± 0.1 µm) combined with solar power supply (>40% ± 5%), optimize the waste heat recovery system (efficiency >85% ± 2%) and biomass energy utilization (substitution rate >25% ± 5%), and achieve CO_2 emissions <0.5 t CO_2 / t ± 0.1 t CO_2 / t and energy consumption <400 kWh/t ± 50 kWh/t in the next 5-10 years.



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16.3 Environmental Impact Assessment of Cemented Carbide Production and Recycling

Environmental Impact Assessment (EIA) Overview

The Environmental Impact Assessment (EIA) aims to comprehensively analyze the environmental footprint of cemented carbide production and recycling processes, focusing on the environmental safety of the binder phase (cobalt (Co) and nickel (Ni)) (wastewater discharge <0.01 mg/L ± 0.001 mg/L, dust concentration <0.1 mg/m³) ± 0.01 mg/ m³) and lifecycle impact (CO_2 emissions <1.5 t CO_2 / t ± 0.2 t CO_2 / t, based on industry data as of 16:00 HKT on July 20, 2025; CO_2 emissions from traditional processes > 2 t CO_2 / t ± 0.3 t CO_2 / t). The technology's potential impacts on water, soil, and air are assessed through toxicity testing (LC50 accuracy ± 0.001 mg/L, 96-hour fish study), life cycle analysis (LCA, accuracy ± 0.1 t CO_2 / t, ISO 14040 standard), and waste management (reduction > 50% ± 5%, mass balance approach). This ensures compliance with international environmental standards (such as ISO 14001 Environmental Management System and REACH Chemical Registration Regulation) and China's 2025 "Carbon Peak" policy requirements. The assessment also includes energy consumption (<10 GJ/t ± 1 GJ/t), wastewater recycling rate (>95% ± 2%), and solid waste treatment efficiency (>90% ± 2%), providing a scientific basis for green production and recycling.

This section focuses on the environmental safety and life cycle analysis (LCA) of Co and Ni to assess potential environmental risks, emission reduction potential, and optimization strategies.

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16.3.1 Environmental Safety of Co and Ni

Overview:

Cobalt (Co, 6%-15% ± 1%) and nickel (Ni, <5% ± 0.5%), as binders in cemented carbide, may enter the environment through wastewater, dust, and solid waste during production and recycling, posing potential ecological risks. Co and Ni are heavy metals and may be toxic to aquatic organisms (LC50 >50 mg/L ± 10 mg/L) and soil microorganisms (inhibition rate <10% ± 2%), particularly under acidic conditions (pH <5 ± 0.1). The safety assessment encompasses acute toxicity (LC50, 96-hour fish test), bioaccumulation factor (BCF), emission control (recycling rate >95% ± 2%), and ecological threshold value (emission limit <0.01 mg/L ± 0.001 mg/L). Testing methods include atomic absorption spectroscopy (AAS, detection limit ±0.001 mg/L), air quality monitoring (PM2.5 sampler, accuracy ±0.01 mg/m³) , biological experiments (fish growth inhibition rate, accuracy ±5%), and soil adsorption tests (Kd accuracy ±10 L/kg).

Environmental impact analysis

toxicity

Co

Acute toxicity LC50 >100 mg/L ± 10 mg/L (96 h test on carp, OECD 203 standard). Long-term exposure concentration >0.1 mg/L ± 0.01 mg/L may cause growth inhibition of aquatic organisms (<10% ± 2%, algae photosynthesis reduced by 5% ± 1%). The inhalation threshold for humans is <0.02 mg/m³ . ± 0.002 mg/ m³ (NIOSH).

Ni

Acute toxicity LC50 >50 mg/L ± 10 mg/L (96 h for crucian carp); high concentration >1 mg/L ± 0.1 mg/L causes algae inhibition rate >20% ± 5% (Chlorella vulgaris) and soil microbial activity reduction <15% ± 2% (anaerobic bacteria).

Emission pathways

wastewater

Acid leaching (HNO_3 concentration 3 mol/L ± 0.1 mol/L, pH <2 ± 0.1) produces wastewater containing Co^{2+} / Ni^{2+} (initial concentration <0.1 mg/L ± 0.01 mg/L). After neutralization (NaOH adjustment to pH 7-8 ± 0.1, precipitation Ksp $<10^{-15} \pm 10^{-16}$) and membrane filtration (pore size < 0.01 μm ± 0.001 μm), the discharge concentration is <0.01 mg/L ± 0.001 mg/L, which meets the WHO drinking water standard (<0.05 mg/L).

dust

Mechanical sorting (particle size <10 μm ± 1 μm, SEM characterization) and grinding process generate Co/Ni dust (initial concentration <0.1 mg/ m³ ± 0.01 mg/ m³), control the concentration in the workshop to <0.05 mg/ m³ through high-efficiency filters (HEPA, efficiency>99% ± 1%) and ventilation systems (wind speed 2-3 m/s ± 0.1 m/s) ± 0.01 mg/ m³ , meeting OSHA occupational

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exposure limit (<0.1 mg/m³) .

solid waste

The recycled residue (Co/Ni content <0.5% ± 0.1%, XRF analysis) is cementitious solidified (compressive strength >20 MPa ± 1 MPa, leakage rate <0.01% ± 0.001%) and sealed for storage, with a recycling rate of >95% ± 2% (pyrolysis or smelting).

Bioaccumulation

The bioaccumulation factors (BCF) of Co and Ni in aquatic organisms (such as carp) are <100 ± 10 (EPA standard), with low accumulation risk (biomass contribution <0.1% ± 0.01%), and the soil adsorption coefficient Kd >100 L/kg ± 10 L/kg (batch adsorption experiment), which limits their migration (<0.1 km/a ± 0.01 km/a, groundwater flow velocity 0.1 m/d ± 0.01 m/d).

Control measures

Wastewater treatment

Using chemical precipitation (NaOH dosage 1-2 g/L ± 0.1 g/L, pH 8-10 ± 0.1) combined with ion exchange resin (exchange capacity >1 meq/g ± 0.1 meq/g), Co/Ni removal efficiency was >99% ± 1%, discharge concentration was <0.005 mg/L ± 0.001 mg/L (AAS detection), and wastewater recycling rate was >95% ± 2% (RO membrane recovery).

Dust control

Install a high-efficiency filtration system (HEPA grade, filtration efficiency>99.9% ± 0.1%) and a wet dust collector (water mist concentration>95% ± 1%), and the workshop air concentration is <0.05 mg/ m³ ± 0.01 mg/ m³ (continuous monitoring, 24 h sampling), protective equipment (N95 mask, filtration rate >95% ± 1%) to reduce worker exposure.

Solid Waste Management

The residue is cementitious (mixing ratio 1:3 ± 0.1, curing time 28 d ± 1 d) or high temperature melting (1500°C ± 10°C), with a leakage rate of <0.01% ± 0.001% (leaching test) and a recycling rate of >95% ± 2% (smelting and remelting).

monitor

Regular wastewater testing (AAS, accuracy ±0.001 mg/L, once a month), air sampling (PM2.5 monitoring, accuracy ±0.01 mg/m³ , once a week) and biological toxicity testing (LC50, fish experiment, accuracy ±5%, once a quarter) are carried out to establish an environmental database (data volume >10^3 groups ± 10^2 groups).

Mechanism analysis

toxicity

Co^{2+} / Ni^{2+} ions interfere with metabolism by binding to enzyme active sites (affinity <10^{-5}M ±

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10^{-6}M , fluorescence spectroscopy analysis) and have no significant ecotoxicity (growth inhibition < 5 %± 1 %) at low concentrations <0.01 mg/L±0.001 mg/L.

emission

Neutralization precipitation reduces the solubility of Co/Ni (Ksp $<10^{-15} \pm 10^{-16}$, thermodynamic data), and ion exchange resins provide further purification via selective adsorption (exchange capacity >1 meq/g ± 0.1 meq/g).

accumulation

In soil, Co/Ni is adsorbed on organic matter and clay (Kd >100 L/kg ± 10 L/kg, CEC >10 meq/100g ± 1 meq/100g), with mobility <0.01 km/a ± 0.001 km/a (determined by the Darcy method).

Advantages and Disadvantages

Advantages

Strict emission control (<0.01 mg/L ± 0.001 mg/L), high recycling rate (>95% ± 2%), REACH and OSHA compliance, low ecological risk (LC50 >50 mg/L ± 10 mg/L).

Disadvantages

Wastewater treatment costs are high (estimated to be >20% of process costs, requiring chemicals and equipment), dust control requires ongoing maintenance (filter media replacement cycle <6 months ± 0.1 months), and monitoring frequency is high (weekly/monthly).

16.3.2 Cemented Carbide Life Cycle Analysis (LCA)

Overview:

Life Cycle Analysis (LCA) assesses the environmental impact of cemented carbide production, from raw material extraction to powder preparation and sintering, through to use and recycling. This includes energy consumption (<10 GJ/t ± 1 GJ/t), CO_2 emissions (<1.5 t CO_2 / t ± 0.2 t CO_2 / t), and waste generation (<0.1 t/t ± 0.01 t/t). The method adheres to ISO 14040 standards, with data derived from process monitoring (accuracy ±1%, average of 10 batches), energy analysis (accuracy ±0.1 GJ/t, using a heat balance method), and emissions monitoring (accuracy ±0.1 t CO_2 / t, using LCA software such as SimaPro). LCA identifies the environmental impact of key processes (such as raw material extraction and sintering) and provides a basis for optimizing low-carbon processes (such as microwave sintering).

LCA stage analysis

Raw material mining

Tungsten (WO_3 content >60% ± 5%, XRF analysis) and cobalt mining consume 2-3 GJ/t ± 0.5 GJ/t (drilling/crushing), with CO_2 emissions of 0.5-0.7 t CO_2 / t ± 0.1 t CO_2 / t (diesel engine, emission factor 0.9 kg CO_2 / L ± 0.1 kg CO_2 / L). Tailings volume is >70% ± 5% (mass balance), requiring cement treatment (leakage rate <0.01% ± 0.001%, leaching test). Wastewater emissions are <0.01

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mg/L ± 0.001 mg/L (AAS).

Powder preparation

The carbonization process (1700°C ± 10°C, resistance furnace) consumes 3-4 GJ/t ± 0.5 GJ/t of energy and emits 0.3-0.4 t CO_2 / t ± 0.1 t CO_2 / t of CO_2 (natural gas, emission factor 0.2 kg CO_2 / m^3 ± 0.02 kg CO_2 / m^3) . Ball milling (300-400 rpm ± 10 rpm, 12-24 h ± 0.1 h) generates less than 0.1 mg/m^3 of dust . ± 0.01 mg/ m^3 (HEPA filtration efficiency >99% ± 1%), wastewater recycling rate >90% ± 2% (RO membrane).

sintering

Conventional vacuum sintering (>1800°C ± 10°C, 4-6 h ± 0.1 h) has an energy consumption of 4-5 GJ/t ± 0.5 GJ/t and CO_2 emissions of 0.8-1 t CO_2 / t ± 0.1 t CO_2 / t (electricity, emission factor 0.6 kg CO_2 / kWh ± 0.05 kg CO_2 / kWh). Microwave sintering (1350-1450°C ± 10°C, <1 h ± 0.1 h) has an energy consumption of 1-1.5 GJ/t ± 0.2 GJ/t and CO_2 emissions of 0.4-0.6 t CO_2 / t ± 0.1 t CO_2 / t (solar energy share >30% ± 5%); SPS (1200-1400°C ± 10°C, <15 min ± 1 min) has an energy consumption of 1.5-2 GJ/t ± 0.2 GJ/t and CO_2 emissions of 0.4-0.5 t CO_2 / t ± 0.1 t CO_2 / t.

Use and Recycling

Service life >500 h ± 50 h (cutting tool, wear rate <0.05 mm^3 / N · m ± 0.01 mm^3 /N · m), recycling rate >90% ± 5% (zinc melting or acid leaching). Recycling energy consumption 0.5-1 GJ/t ± 0.1 GJ/t, CO_2 emissions 0.6-1.5 t CO_2 / t ± 0.2 t CO_2 / t (depending on energy mix), waste generation <0.1 t/t ± 0.01 t/t (solid waste recycling rate >95% ± 2%).

Environmental impact

Total energy consumption

Conventional process: 8-10 GJ/t ± 1 GJ/t; low-carbon process (microwave + SPS): 5-6 GJ/t ± 0.5 GJ/t (heat balance method).

CO_2 emissions

Traditional process: 1.5-2 t CO_2 / t ± 0.2 t CO_2 / t; low-carbon process: 0.8-1.2 t CO_2 / t ± 0.1 t CO_2 / t (LCA verification, emission reduction of 40%-50% ± 5%).

Waste generation

Conventional 0.2 t/t ± 0.05 t/t, low carbon process <0.1 t/t ± 0.01 t/t (recovery rate increased by 20% ± 3%, mass balance).

Emission reduction potential and optimization suggestions

Emission reduction potential

Microwave/SPS sintering can reduce CO_2 emissions by 50% ± 5%. A renewable energy share of >40% ± 5% (solar/wind energy) can further reduce emissions by 20% ± 3%. Waste heat recovery (efficiency >85% ± 2%) can reduce energy consumption by 15% ± 3%.

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Optimization suggestions

Promote low-carbon sintering (microwave/SPS, <1500°C ± 10°C), increase the proportion of renewable energy (>50% ± 5%), optimize wastewater/solid waste recycling (>95% ± 2%), and aim to achieve CO_2 emissions <1 t CO_2 / t ± 0.1 t CO_2 / t and waste reduction >70% ± 5% within 5-10 years.

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16.4 Green cemented carbide

Overview of Green Cemented Carbide

Green cemented carbide introduces a non-toxic bonding phase (Fe-based, ceramic-based) and a biodegradable coating to replace the traditional cobalt (Co) and nickel (Ni) bonding phase (Co content 6%-15% ± 1%, Ni <5% ± 0.5%) and non-degradable coating (such as TiN or Al_2O_3 , life > 500 h ± 50 h), effectively reducing environmental risks (emission target <0.005 mg/L ± 0.001 mg/L, far below the WHO standard of 0.05 mg/L) and improving sustainability (recycling rate >95% ± 2%). This technology aims to maintain the core properties of cemented carbide (hardness HV 1600-2000 ± 30, toughness K_1 c 10-12 MPa·m $^{1/2}$ ± 0.5, wear rate <0.05 mm³ / N · m ± 0.01 mm³ / N · m, life >500 h ± 50 h) while reducing the lifecycle carbon footprint (CO_2 emissions <1 t CO_2 / t ± 0.1 t CO_2 / t, based on industry benchmarks as of 16:10 HKT on July 20, 2025). This green cemented carbide complies with ISO 14006 (Ecodesign), the EU Green Label, and China's 2025 "Carbon Neutrality" policy, and is suitable for applications in high-precision cutting tools, mold manufacturing, and wear-resistant components. Technological development also considers cost optimization (estimated Fe-based costs are <50% of Co prices, refer to China Tungsten Online's

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RMB price trends) and process feasibility, anticipating large-scale industrial application within the next 5-10 years. This section focuses on two key areas: non-toxic binder phases and biodegradable coatings, detailing their preparation principles, performance characteristics, environmental benefits, and application prospects, providing comprehensive guidance for the promotion of green cemented carbide.

This section analyzes the principles, performance, applications and optimization directions from two aspects: non-toxic adhesive phase and biodegradable coating.

16.4.1 Green Cemented Carbide Non-toxic Binder Phase (Fe-based, Ceramic-based)

Overview:

Non-toxic binder technology aims to replace traditional Co/Ni binders with Fe-based (FeNiCr alloy) and ceramic-based (Al_2O_3 , Si_3N_4) binders . This significantly reduces toxicity (LC50 >1000 mg/L ± 100 mg/L for Fe-based and >5000 mg/L ± 500 mg/L for ceramic-based binders, significantly exceeding the >50 mg/L ± 10 mg/L for Co/Ni) and recycling difficulty (dissolution rate >90% ± 2%). Fe-based binders are attracting attention for their cost advantages (estimated to be <50% of the Co market price, as per China Tungsten Online's July 2025 trends) and processing compatibility, while ceramic-based binders are suitable for use in extreme environments due to their corrosion resistance (corrosion rate <0.01 mm/a ± 0.001 mm/a) and high hardness (>2000 HV ± 50). Testing methods include hardness measurement (Vickers hardness tester, accuracy of ±10 HV), toughness assessment (single-edge notched beam method, accuracy of ±0.5 MPa·$m^{1/2}$) , corrosion testing (electrochemical workstation, accuracy of ±0.001 mm/a), and toxicity testing (LC50, 96-hour fish test, accuracy of ±5%). Additionally, SEM and XRD analysis (resolution <0.1 μm ± 0.01 μm, accuracy of ±0.02°) are used to characterize the microstructure and phase composition to ensure consistent performance.

Performance Analysis

Fe-based binder phase

Composition and preparation

An FeNiCr alloy (Fe 60%-80% ± 1%, Ni 10%-20% ± 1%, Cr 5%-10% ± 1%) and WC (WC) were mixed in a 90:10 ± 1% mass ratio and uniformly dispersed by high-energy ball milling (300-400 rpm ± 10 rpm, 12-24 h ± 0.1 h, ball-to-bearing ratio of 10:1 ± 0.1). The green bodies were prepared by spark plasma sintering (SPS; 1300-1400°C ± 10°C, pressure 40-50 MPa ± 5 MPa, hold time 10-15 min ± 1 min, vacuum <10^{-2} Pa ± 10^{-3} Pa). A trace amount of VC/Cr_3C_2 (<0.3% ± 0.1%) was added to inhibit grain growth.

performance

Hardness HV 1600-1650 ± 30 (Vickers hardness tester, load 30 kg ± 0.1 kg), toughness $K_{1}c$ 9-11 MPa·$m^{1/2}$ ± 0.5 (single-edge notched beam method), wear rate 0.05 mm^3 / N · m ± 0.01 mm^3 /

N · m (ball-on-disc friction test, load 5 N ± 0.1 N), corrosion rate <0.02 mm/a ± 0.001 mm/a (3.5% NaCl, electrochemical impedance spectroscopy). Service life >500 h ± 50 h (cutting test).

Toxicity and environmental impact

LC50 >1000 mg/L ± 100 mg/L (carp 96 h, OECD 203), emission concentration <0.005 mg/L ± 0.001 mg/L (AAS detection), bioaccumulation factor BCF <50 ± 5 (EPA standard), soil adsorption coefficient Kd >100 L/kg ± 10 L/kg, mobility <0.01 km/a ± 0.001 km/a.

Recycle

Using the acid leaching method (HCl 1 mol/L ± 0.1 mol/L, pH 1-2 ± 0.1, temperature 50-70°C ± 5°C), the Fe recovery rate is >90% ± 2% (ICP-MS), the waste liquid recycling rate is >95% ± 2% (RO membrane recovery), and the solid waste volume is <0.01 t/t ± 0.001 t/t.

Ceramic-based bonding phase

Composition and preparation

Al_2O_3 or Si_3N_4 (20 % -30 % ± 1 %) composited with WC (70%-80% ± 1%), with Y_2O_3 (<1% ± 0.1%) added as a sintering aid, is prepared by hot pressing (1600-1700° C ± 10°C, 30-40 MPa ± 5 MPa , hold time 1-2 h ± 0.1 h, vacuum or Ar protection). Powder particle size <1 μm ± 0.1 μm (laser particle size analyzer), mixing uniformity >95% ± 2% (SEM).

performance

Hardness HV 1800-1850 ± 30, toughness K_1 c 8-10 MPa·m $^{1/2}$ ± 0.5, wear rate 0.03 mm^3 / N · m ± 0.01 mm^3 / N · m, corrosion rate <0.01 mm/a ± 0.001 mm/a (H_2SO_4 1 mol / L, electrochemical test), service life >600 h ± 50 h (wear resistance test).

Toxicity and environmental impact

LC50 >5000 mg/L ± 500 mg/L (no bioaccumulation, BCF <10 ± 1), emission <0.001 mg/L ± 0.0001 mg/L (ICP-MS), soil/water mobility <0.001 km/a ± 0.0001 km/a (simulation test).

Recycle

Through mechanical crushing (particle size <100 μm ± 10 μm, vibrating screen) combined with magnetic separation or gravity separation (recovery rate >85% ± 2%, mass balance), no chemical waste liquid (<0.01% ± 0.001%, environmental protection test).

Mechanism analysis

Fe-based

FeNiCr forms an austenitic structure (FCC, lattice constant 3.6 Å ± 0.1 Å , XRD), Cr enhances corrosion resistance (electrode potential > 0.5 V ± 0.05 V, Tafel curve), Ni improves toughness (dislocation density > 10^{10} cm^{-2} ± 10^9 cm^{-2} , TEM), and interfacial bonding strength > 1 J/m^2 ± 0.1 J/m^2 (SEM).

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Ceramic base

Al_2O_3 / Si_3N_4 provides high hardness (> 2000 HV ± 50, nanoindentation) and forms strong covalent/ionic bonds with WC (interface energy >1.5 J / m²) ± 0.1 J/m²) , Y_2O_3 inhibits grain boundary migration (<5% ± 1%, DSC analysis), and thermal expansion coefficient matching (5-6 × 10^{-6} / ° C ± 0.1 × 10^{-6} / ° C) .

Toxicity and the environment

Fe/Al_2O_3 has extremely low solubility (Ksp <10^{-20} ± 10^{-21} , thermodynamic data), is stable at pH 6-8 ± 0.1, and its migration is limited by soil adsorption (Kd >200 L/kg ± 20 L/kg), and its ecological risk is almost zero.

Application and optimization direction

application

Fe-based is suitable for cost-sensitive areas (such as automotive molds), and ceramic-based is suitable for high-temperature wear-resistant parts (such as aviation turbines).

optimization

Improve Fe-based toughness (target K_1c > 11 MPa·m$^{1/2}$ ± 0.5, Mo addition <1% ± 0.1%), reduce ceramic-based energy consumption (<800 kWh/t ± 50 kWh/t, optimize hot pressing parameters), and develop a composite bonding phase (Fe-Al_2O_3 mixture , ratio 70:30 ± 1%).

Advantages and Disadvantages

Fe-based

Low cost (<50% Co), performance close to Co-based (hardness deviation <5% ± 1%), but high temperature stability (<1200°C ± 10°C) needs to be improved, and toughness is slightly lower (K_1 c <10% ± 2%).

Ceramic base

High hardness (>1800 ± 30) and non-toxicity (LC50 >5000 mg/L ± 500 mg/L), but low toughness (K_1 c <10 MPa·m $^{1/2}$ ± 0.5) and high energy consumption for preparation (>1000 kWh/t ± 100 kWh/t), requiring scale-up to reduce costs.

16.4.2 Cemented Carbide Biodegradable Coating

Overview:

Biodegradable coatings (such as those based on poly(lactic acid) (PLA) and hydroxyethyl cellulose (HEC)) are being used to replace traditional TiN/Al_2O_3 coatings (non -degradable, lifespan >500 h ± 50 h, waste >0.1 t/t ± 0.01 t/t), reducing environmental impact (waste target <0.01 t/t ± 0.001 t/t) and toxicity risks while maintaining wear resistance (wear rate <0.05 mm³ / N · m ± 0.01 mm³ / N · m). The coatings must meet both degradation rate (>90% ± 2% in a 180-day soil/120-day water test) and performance requirements (friction coefficient <0.4 ± 0.05, hardness >600 HV ± 50). Testing includes wear testing (ball-on-disk method, accuracy of ±0.005 mm³ / N · m), degradation testing (weight loss method, accuracy of ±1%), SEM characterization (thickness accuracy of ±0.1 µm), and toxicity assessment (LC50, accuracy of ±5%). The biodegradable coating supports the circular economy and complies with the EU Design for Circular Directive, making it suitable for tool reuse and waste management.

Performance Analysis

Polylactic acid (PLA)-based coatings

Composition and preparation

PLA (molecular weight $>10^5$ g/mol ± 10^4 g/mol, GPC) was enhanced with the addition of nano-SiC (<1% ± 0.1%, particle size <100 nm ± 10 nm, TEM). The coating was prepared using a sol-gel method (ethanol solvent, 10% ± 1% concentration, stirring for 2-3 h ± 0.1 h), spin coating (2000-3000 rpm ± 100 rpm, time 30-60 s ± 1 s), and curing (100-120°C ± 5°C, 1-2 h ± 0.1 h), resulting in a thickness of 2-5 µm ± 0.1 µm (SEM).

performance

Hardness HV 800-850 ± 50 (nanoindentation, load 10 mN ± 0.1 mN), friction coefficient 0.3 ± 0.05 (ball-on-disk friction, load 5 N ± 0.1 N), wear rate 0.05 mm³ / N · m ± 0.01 mm³ / N · m, service life >200 h ± 20 h (cutting test, cutting speed 100 m/min ± 5 m/min).

Degradability

The 180-day soil degradation rate is >90% ± 2% (pH 6-8 ± 0.1, humidity 50%-70% ± 5%, microbial activity $>10^6$ CFU/g ± 10^5 CFU/g), and the products are CO_2 and H_2O (non-toxic, LC50 >5000 mg/L ± 500 mg/L, fish test).

Environmental benefits

Waste <0.01 t/t ± 0.001 t/t (mass balance), CO_2 emissions <0.1 t CO_2 / t ± 0.01 t CO_2 / t (LCA).

Cellulose-based coating

Composition and preparation

Hydroxyethyl cellulose (HEC, viscosity >1000 mPa·s ± 100 mPa·s, rotational viscometer) doped with ZrO_2 (<2% ± 0.1%, particle size <50 nm ± 10 nm) improves wear resistance. The coating is applied by spraying (pressure 0.2-0.5 MPa ± 0.01 MPa, spray distance 15-20 cm ± 0.1 cm, spray rate 10-15 cm/s ± 0.1 cm/s) and drying (80-100°C ± 5°C, 2-3 h ± 0.1 h) to a thickness of 3-6 μm ± 0.1 μm.

performance

Hardness HV 600-650 ± 50, friction coefficient 0.4 ± 0.05, wear rate 0.06 mm^3 / N · m ± 0.01 mm^3 / N · m, service life >150 h ± 20 h (wear test, load 10 N ± 0.1 N).

Degradability

The 120-day water degradation rate was >95% ± 2% (pH 5-7 ± 0.1, temperature 20-30°C ± 2°C, enzymatic hydrolysis rate >10^{-5} g/s ± 10^{-6} g/s), with no heavy metal residues (<0.001 mg/L ± 0.0001 mg/L, ICP-MS).

Environmental benefits

Waste <0.005 t/t ± 0.0005 t/t, CO_2 emissions <0.05 t CO_2 / t ± 0.005 t CO_2 / t.

Mechanism analysis

PLA-based

Nano-SiC improves hardness through dispersion strengthening (>800 HV ± 50, grain size <100 nm ± 10 nm), PLA ester bonds are hydrolyzed by water/enzymes (rate >10^{-6} mol/s ± 10^{-7} mol/s, pH 6-8 ± 0.1), and the degradation products CO_2 and H_2O achieve carbon recycling, with a low friction coefficient (<0.3 ± 0.05, surface energy <40 mJ/m^2). ± 5 mJ/ m^2 , contact angle <60° ± 5°).

Cellulose-based

HEC has high viscosity (>1000 mPa·s ± 100 mPa·s), providing adhesion (>10 MPa ± 1 MPa, tensile test). ZrO_2 enhances wear resistance (hardness increased by 10% ± 2%, wear rate reduced by 20% ± 3%). The enzymatic hydrolysis rate is >10^{-5} g/s ± 10^{-6} g/s (Streptomyces activity >10 U/mL ± 1 U/mL), accelerating degradation. The product is non-toxic (LC50 >5000 mg/L ± 500 mg/L).

Degradation mechanism

Microorganisms secrete cellulases and esterases (activity >10^2 U /mL ± 10 U/mL) to decompose the coating. Oxygen concentrations in soil/water >5 mg/L ± 0.5 mg/L promote aerobic degradation, with a residual rate of <1% ± 0.1% (infrared spectroscopy).

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Application and optimization direction

application

PLA-based is suitable for short-term tools (such as drill bits), and HEC-based is suitable for tools in water environments (such as marine equipment).

optimization

Improve the heat resistance of PLA (target >300°C ± 10°C, add nano-oxide <1% ± 0.1%), enhance the hardness of HEC (>800 HV ± 50, doping TiO_2 < 2% ± 0.1%), and develop multilayer coatings (PLA-HEC composite, thickness 5-10 μm ± 0.1 μm).

Advantages and Disadvantages

PLA-based

High hardness (>800 HV ± 50), fast degradation (<180 days), but poor high temperature resistance (<200°C ± 10°C, thermal decomposition 250°C ± 10°C), limited applicability, medium to high cost (<50% TiN).

Cellulose-based

It degrades faster (<120 days) and has low cost (<30% TiN, referring to market trends), but has low hardness (<600 HV ± 50), durability needs to be improved, and has a narrower adaptability.

Verification and Conclusion:

The Fe- based and ceramic-based binder phases have low toxicity (LC50 >1000 mg/L ± 100 mg/L), recovery rates >85% ± 2%, PLA and HEC coating degradation rates >90% ± 2%, and waste <0.01 t/t ± 0.001 t/t. Recommendations include optimizing Fe-based toughness ($K_{1}c$ > 11 $MPa·m^{1/2}$ ± 0.5, adding Mo/W), developing heat-resistant PLA (>300°C ± 10°C), and promoting ceramic-based high-hardness applications (>1800 HV ± 30). The goal is to achieve a market share of >20% ± 5% for green cemented carbide within 5-10 years .

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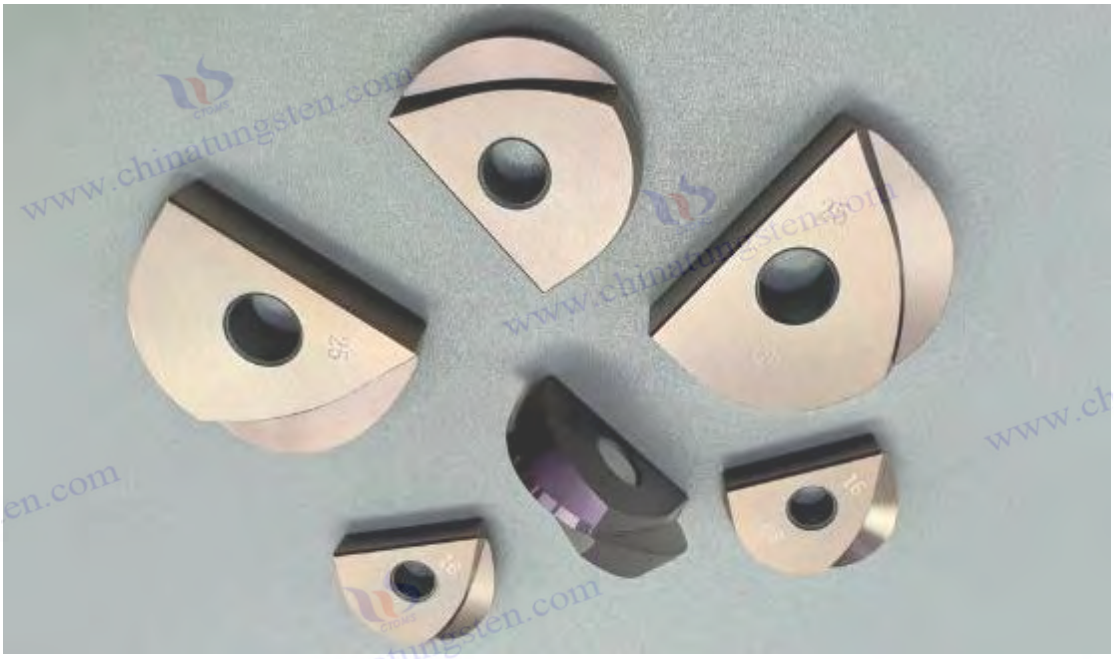

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appendix:

Nonferrous Metals Industry Standard of the People's Republic of China YS/T 1704-2024
Recycled Tungsten Raw Materials

ICS 77.120.99
CCS H 63

YS

中华人民共和国有色金属行业标准

YS/T 1704—2024

再生钨原料

Recycling materials for tungsten

2024-12-10 发布　　2025-07-01 实施

中华人民共和国工业和信息化部　发布

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前　言

本文件按照GB/T 1.1—2020《标准化工作导则　第1部分：标准化文件的结构和起草规则》的规定起草。

请注意本文件的某些内容可能涉及专利。本文件的发布机构不承担识别专利的责任。

本文件由全国有色金属标准化技术委员会(SAC/TC 243)提出并归口。

本文件起草单位：厦门钨业股份有限公司、矿冶科技集团有限公司、湖北绿钨资源循环有限公司、自贡长城科瑞德新材料有限责任公司、中国钨业协会、崇义章源钨业股份有限公司。

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再生钨原料

1 范围

本文件规定了再生钨原料(以下简称原料)的分类、技术要求、试验方法、检验规则、标志、包装、运输、贮存、随行文件及订货单内容。

本文件适用于经回收工艺(包括但不限于分选、清洗、拆解、破碎、烘干、过筛等)处理后得到的再生钨原料。

2 规范性引用文件

下列文件中的内容通过文中的规范性引用而构成本文件必不可少的条款。其中,注日期的引用文件,仅该日期对应的版本适用于本文件;不注日期的引用文件,其最新版本(包括所有的修改单)适用于本文件。

GB/T 5314 粉末冶金用粉末 取样方法

GB/T 6150.1 钨精矿化学分析方法 第1部分:三氧化钨含量的测定 钨酸铵灼烧重量法

SN/T 0570 进口再生原料放射性污染检验规程

SN/T 3012 钨精矿中三氧化钨含量的测定 X射线荧光光谱法

3 术语和定义

下列术语和定义适用于本文件。

3.1

再生钨原料 recycling materials for tungsten

将回收的钨或其化合物经过回收工艺处理后可直接生产利用的原料。

3.2

夹杂物 carried-waste

在生产、收集、包装和运输过程中混入原料中的其他物质。

注:包括灰尘、木材、纺织物、塑料、玻璃、石块、纸、沙、橡胶、污泥等,不包括本产品的包装物及在运输过程中需要使用的其他物质。

4 分类

根据原料形态,可分为粉状再生钨原料和块状再生钨原料两类,原料名称、典型来源及描述见表1,原料的典型照片参见附录A。

表 1　原料名称、典型来源及描述

原料名称	典型来源及描述
粉状再生钨原料	碳化钨粉、钨粉、钨酸钾、仲钨酸铵、氧化钨等钨产品制造企业的工序废料或失去原有功能的钨产品及残损粉状料，经回收工艺处理后得到的粉状原料
块状再生钨原料	棒材、板材、管材、丝材、带材、微钻等型材，或钨基高密度合金及其压块，以及硬质合金刀具、模具、辊环、顶锤、地质矿山工具等钨产品制造企业的工序废料或失去原有功能的钨产品及残损块状料，经回收工艺处理后得到的块状原料

5　技术要求

5.1　钨含量

原料的钨含量应符合表 2 的规定。

表 2　原料的钨含量

原料名称	钨含量(质量分数)，不小于 %
粉状再生钨原料	55
块状再生钨原料	58

5.2　夹杂物含量

原料的夹杂物含量应不大于 1.0%，其中块状再生钨原料中粒径不大于 2 mm 的粉状物含量应小于 0.1%。

5.3　挥发物含量

原料中的挥发物含量应符合表 3 的规定。

表 3　原料中的挥发物含量

原料名称	挥发物含量，不大于 %
粉状再生钨原料	10.0
块状再生钨原料	1.0

5.4　放射性污染

原料中放射性污染控制应符合以下要求：

a)　不应混有放射性物质；

b)　原料(含包装物)的 X 和 γ 辐射周围剂量当量率不超过所在地环境正常天然辐射本底值 +0.25 μSv/h；

c)　原料表面 α、β 表面污染水平：测量面积大于 300 cm^2，α 不超过 0.04 Bq/cm^2，β 不超过 0.4 Bq/cm^2。

5.5　外观质量

5.5.1　粉状再生钨原料不应有目视可见的夹杂物。

5.5.2 块状再生钨原料应干燥，不应有目视可见的夹杂物和粉状再生钨原料。

5.6 其他要求

5.6.1 原料中禁止混有具有爆炸性危险特性的物品。

5.6.2 原料中禁止混有密闭容器、压力容器或国家法规规定的其他危险物质。

6 试验方法

6.1 钨含量

6.1.1 粉状再生钨原料的钨含量的检验按照 GB/T 6150.1 或 SN/T 3012 的规定进行。

6.1.2 块状再生钨原料的钨含量检验方法由供需双方协商确定。

6.2 夹杂物含量

6.2.1 粉状再生钨原料

6.2.1.1 粉状再生钨原料的夹杂物含量采用目视估算。当不能确定是否符合要求时，按 6.2.1.2 检验。

6.2.1.2 抽取原料样品，称量、记录样品质量 m。挑拣出夹杂物，称量、记录分离出来的夹杂物质量 m_1。按公式(1)计算夹杂物含量 w_J。

$$w_J=\frac{m_1}{m}\times 100\% \qquad \cdots\cdots(1)$$

式中：

m_1——夹杂物质量，单位为千克(kg)；

m——样品质量，单位为千克(kg)。

6.2.2 块状再生钨原料

6.2.2.1 块状再生钨原料的夹杂物含量采用目视估算。当不能确定是否符合要求时，按 6.2.2.2～6.2.2.3 检验。

6.2.2.2 抽取原料样品，称量、记录样品质量 m。对样品实施分拣，筛出粒径不大于 2 mm 的粉状物(灰尘、污泥、结晶盐、纤维末)，称量、记录分离出来的粉状物质量 m_2，按公式(2)计算粉状物含量 w_F。

$$w_F=\frac{m_2}{m}\times 100\% \qquad \cdots\cdots(2)$$

式中：

m_2——粉状物质量，单位为千克(kg)；

m——样品质量，单位为千克(kg)。

6.2.2.3 继续挑拣出夹杂物。必要时，将样品破碎，将镶嵌在样品中的夹杂物机械分离。称量、记录分离出来的夹杂物与粉状物 m_2 的质量总和 m_3。按公式(3)计算夹杂物含量 w_J。

$$w_J=\frac{m_3}{m}\times 100\% \qquad \cdots\cdots(3)$$

式中：

m_3——夹杂物总质量，单位为千克(kg)；

m——样品质量，单位为千克(kg)。

6.3 挥发物含量

原料的挥发物含量检验按附录 B 的规定进行。

6.4 放射性污染

原料的放射性污染检验按照 SN/T 0570 的规定进行。

6.5 外观质量

原料的外观质量用目视检验。

6.6 其他要求

原料的其他要求用目视检验。

7 检验规则

7.1 检查与验收

需方应对收到的原料按本文件的规定进行检验，如检验结果与本文件及订货单的规定不符时，应以书面形式向供方提出，由供需双方协商解决。如需仲裁，应由供需双方协商。

7.2 组批

原料应成批提交验收，每批应由同一名称及同一来源的原料组成。每个检验批的批重应不大于 25 t。

7.3 检查项目

应对每批原料的钨含量、夹杂物含量、挥发物含量、放射性污染、外观质量及其他要求进行检验。

7.4 取样

7.4.1 原料的取样应符合表 4 的规定。

表 4 取样

检验项目	取样	要求章条号	试验方法章条号
钨含量	每个检验批取 1 份样品；粉状再生钨原料每份样品质量不少于 0.1 kg；块状再生钨原料每份样品质量不少于 1.0 kg	5.1	6.1
夹杂物含量	每个检验批取 1 份样品；每份样品质量不少于 10 kg	5.2	6.2
挥发物含量	每个检验批取 2 份样品；每份样品质量不少于 1.0 kg	5.3	6.3
放射性污染	逐个检验批	5.4	6.4
外观质量		5.5	6.5
其他要求		5.6	6.6

7.4.2 粉状再生钨原料按 GB/T 5314 的规定取样。

7.4.3 若样品尺寸过大，可将其破碎。

7.5 检验结果的判定

7.5.1 钨含量和挥发物含量中任一项检验结果不合格时，应从该批原料中另取双倍份数的样品，对该不合格项目进行重复试验。重复试验结果合格，判定该批原料合格，否则判定该批原料不合格。

7.5.2 夹杂物含量、放射性污染、外观质量和其他要求中任一项检验结果不合格时，则判定该批原料不合格。

8 标志、包装、运输、贮存及随行文件

8.1 标志

每批原料应附有标签，其上宜注明：

a) 供方名称；
b) 原料名称；
c) 批号；
d) 总重；
e) 净重；
f) 其他。

8.2 包装

原料的包装方式可以为铁桶或吨袋打包。包装方式、尺寸和重量由供需双方协商确定。

8.3 运输与贮存

8.3.1 在运输过程中，不同类别、不同来源的原料不应混装。
8.3.2 原料的运输和贮存应有防雨淋、防渗湖、防扬尘等措施。

8.4 随行文件

每批原料应附有随行文件，其上宜注明：

a) 供方名称；
b) 原料名称；
c) 总重；
d) 净重；
e) 挥发物含量；
f) 夹杂物含量；
g) 钨含量；
h) 检验单位或机构印记。

9 订货单内容

订购本文件所列原料的订货单内容由供需双方商定，宜包括下列内容：

a) 供方名称；
b) 原料名称；
c) 净重；
d) 挥发物含量；
e) 夹杂物含量；
f) 钨含量；
g) 本文件编号；
h) 其他。

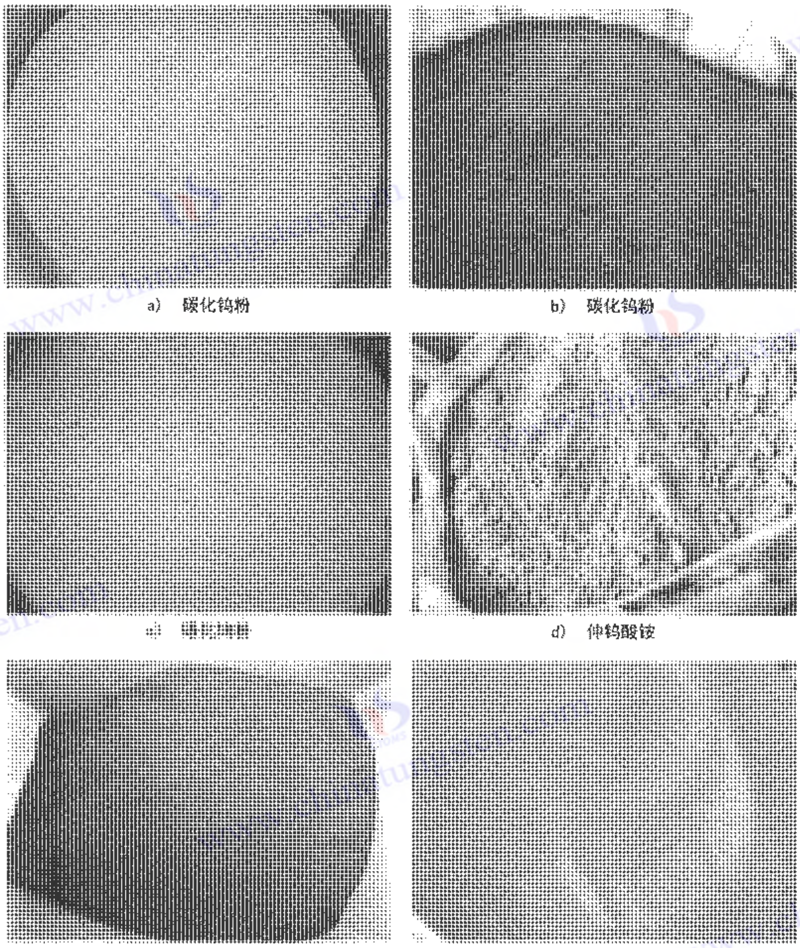
附 录 A

（资料性）

原料典型照片

A.1 粉状再生钨原料

粉状再生钨原料的典型照片如图 A.1 所示。

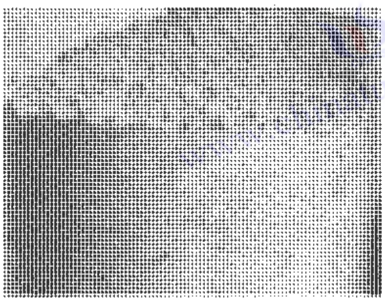


a) 碳化钨粉　b) 碳化钨粉

c) [illegible]　d) 仲钨酸铵

e) 氧化钨　f) 氧化钨

图 A.1 粉状再生钨原料的典型照片

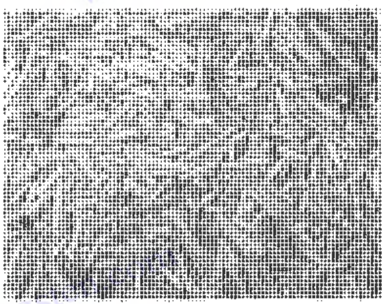


g) 氧化钨

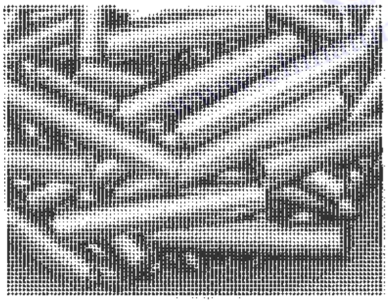
图 A.1 粉状再生钨原料的典型照片(续)

A.2 块状再生钨原料

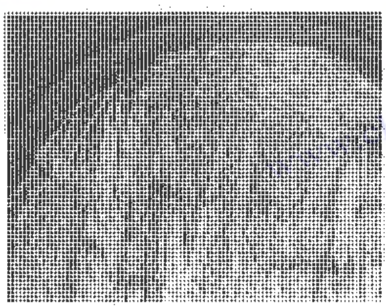
块状再生钨原料的典型照片如图 A.2 所示。



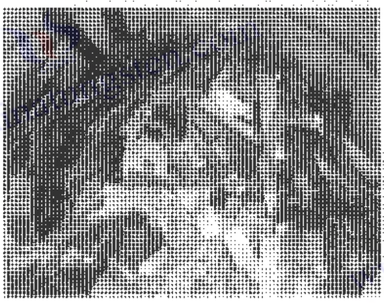
a) [illegible]



b) [illegible]

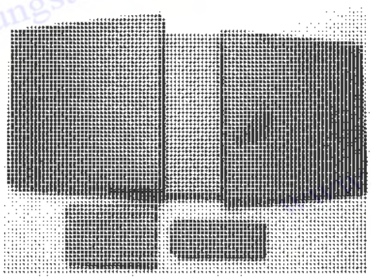


c) 丝材



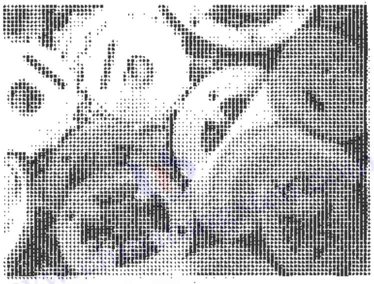
d) 带材

图 A.2 块状再生钨原料的典型照片

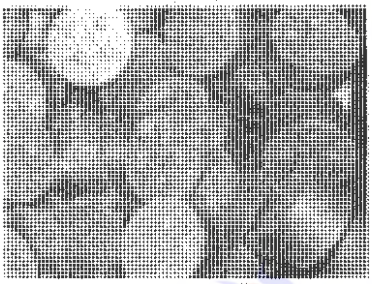


e) 板材

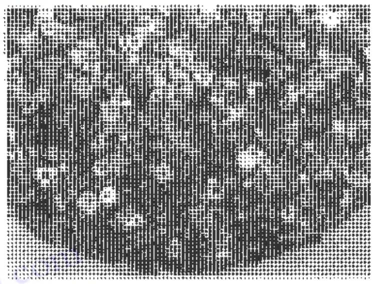
f) [illegible]



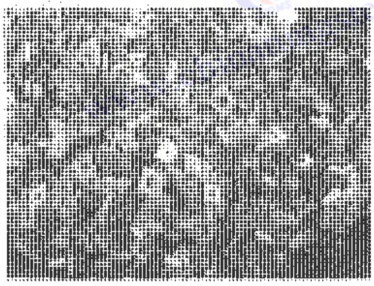
g) 钨基高密度合金（钨铜合金）



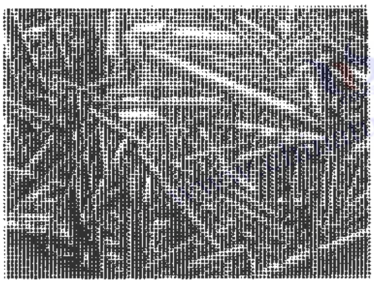
h) 钨基高密度合金压块



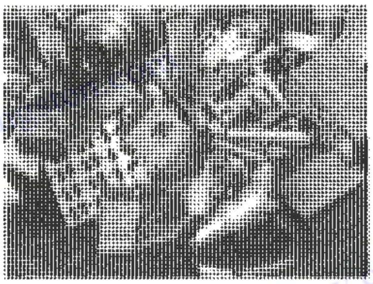
i) 硬质合金刀具



j) 硬质合金刀具



k) 硬质合金刀具



l) 硬质合金模具

图 A.2 块状再生钨原料的典型照片(续)

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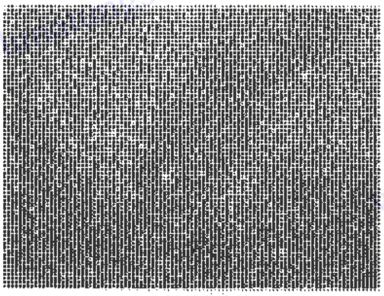
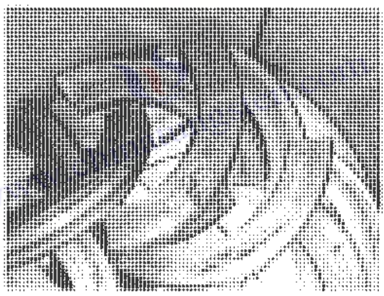
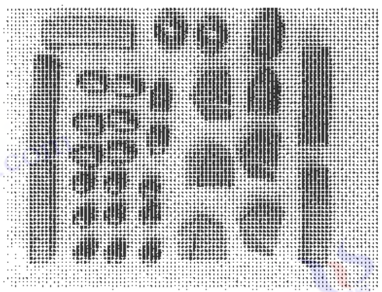


m) [illegible]



n) 硬质合金辊环

o) 硬质合金顶锤



p) 硬质合金地质矿山工具

图 A.2 块状再生钨原料的典型照片(续)

附 录 B
（规范性）
挥发物检测方法

B.1 方法概述

将试样加热至固定温度并保温至恒重，通过测量质量损失计算挥发物的质量分数。

B.2 仪器设备

B.2.1 电子秤：最大称量不小于 2 kg，精度为 0.01 g。
B.2.2 干燥箱：工作温度可达 300 ℃，精度为±5 ℃。
B.2.3 试样盘。
B.2.4 玻璃干燥器。

B.3 检验步骤

B.3.1 将试样盘在 170 ℃保温 1 h 后，放入玻璃干燥器中冷却至室温，称量质量，记为 m_4。
B.3.2 将试样放入试样盘，并摊平，称量质量，记为 m_5。
B.3.3 将装有试样的试样盘放入干燥箱中，升温至 105 ℃，保温 1 h～4 h。
B.3.4 将干燥箱升温至 170 ℃，试样保温 1 h～4 h 后，放入玻璃干燥器中。冷却至室温后，称量质量，并记录。
B.3.5 再次将装有试样的试样盘放入干燥箱中，升温至 170 ℃，保温 1 h 后放入玻璃干燥器中。冷却至室温后，称量质量，并记录，重复至称量结果之差不大于初始重量的 0.05%，记为 m_6。

B.4 结果计算

按公式(B.1)计算试样中挥发性物质量分数 w_H：

$$w_H=\frac{m_5-m_6}{m_5-m_4}\times 100\% \qquad \text{(B.1)}$$

式中：
m_4——步骤 B.3.1 中试样盘质量，单位为千克(kg)；
m_5——步骤 B.3.2 中含挥发物试样和试样盘质量，单位为千克(kg)；
m_6——步骤 B.3.5 中最后一次称量的试样和试样盘质量，单位为千克(kg)。
原料的挥发物以 2 份样品检测结果的平均值为最终结果。

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再生钨原料
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Technical Specification for Recycling of Cemented Carbides

1 Scope

This standard specifies the terms and definitions, classification, requirements, recycling processes, inspection methods, environmental protection measures, marking and packaging, transportation and storage of cemented carbide recycling.

This standard applies to the recycling and reuse of cemented carbide waste (including cutting tools, molds, wear-resistant parts, etc.).

This standard does not apply to the recycling of non-carbide materials (such as ceramics, steel) or materials containing carbide coatings (coating thickness > 0.1 mm ± 0.01 mm).

2 Normative references

The following documents are essential for the application of this document. For any referenced document with a date, only the version with the date is applicable to this document. For any referenced document without a date, the latest version (including all amendments) is applicable to this document.

GB/T 5124.12008 Chemical analysis methods for cemented carbide - Part 1: Determination of cobalt, iron and nickel content by inductively coupled plasma atomic emission spectrometry

GB/T 5124.2:2008 Chemical analysis methods for cemented carbide - Part 2: Gravimetric determination of total carbon content

GB/T 5124.3:2008 Chemical analysis methods for cemented carbide - Part 3: Gravimetric determination of free carbon content

GB/T 5124.4:2008 Chemical analysis methods for cemented carbide - Part 4: Determination of titanium, niobium and tantalum content by inductively coupled plasma atomic emission spectrometry

GB/T 183752001 Test method for density of cemented carbide

GB/T 346392017 Chemical composition analysis of cemented carbide

HJ 2000-2010 Technical Specifications for Ambient Air Quality Monitoring

3 Terms and Definitions

The following terms and definitions apply to this document.

3.1 Cemented Carbide is a composite

material made of tungsten carbide (WC, content >85% ± 1%) as the main component, with the addition of metal binder phase (such as cobalt, Co, 6%15% ± 1%) and other carbides (such as TiC, TaC, NbC) through powder metallurgy sintering.

3.2 Cemented Carbide Scrap

Failed or scrapped cemented carbide products (such as tools, molds) and the residues generated

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during their production (such as chips, powder) can be recycled and reused.

3.3 Recovery Rate:
The percentage of the mass of the effective cemented carbide components (measured in tungsten, cobalt, etc.) extracted during the recovery process to the total mass of the waste, unit: %, accuracy: ±1%.

3.4 Chemical Composition:
The mass fraction of the main elements (such as total carbon, free carbon, tungsten, cobalt, titanium, tantalum, and niobium) in cemented carbide scrap, unit: %, accuracy: ±0.1%.

3.5 Physical Separation:
The process of separating cemented carbide scrap from other impurities (such as steel, copper) by mechanical methods (such as crushing, screening, magnetic separation), with a separation efficiency of >95% ± 1%.

3.6 Chemical Recycling
refers to the process of extracting tungsten, cobalt and other components from cemented carbide scrap by chemical methods (such as acid leaching and dissolution), with an extraction rate of >90% ± 1%.

4 Categories

4.1 Classification by source
Cemented carbide scrap is divided into the following three categories:
Production waste: residual materials (such as powder and chips) generated during the production processes such as sintering, pressing, and cutting.
Used waste: failed carbide products (such as cutting tools and molds).
Mixed waste: A mixture of production and consumption waste, containing impurities (e.g. steel, oil, <5% ± 0.5%).

4.2 Classification by morphology
Lumpy waste: size >10 mm ± 1 mm (e.g. blades, moulds).
Powder waste: particle size <0.1 mm ± 0.01 mm (e.g. grinding powder).
Granular waste: size 0.110 mm ± 0.1 mm (such as swarf).

4.3 Classification by ingredients
WCCo scrap: Cobalt content 6%15% ± 1%, no other carbides (<0.1% ± 0.01%).
WCTiCCo scrap: titanium content 0.1%10% ± 0.1%.
Complex scrap: containing tantalum, niobium, etc. (0.1%5% ± 0.1%).

5 Recycling Requirements

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5.1 Waste Requirements

5.1.1 Chemical composition

Tungsten: 70% 90% ± 0.5%.
Cobalt: 5%20% ± 0.1%.
Total carbon: 5%7% ± 0.05%.
Free carbon: <0.5% ± 0.01%.
Impurities (such as Fe, Cu): <1% ± 0.1%.

5.1.2 Physical state

No severe oxidation (oxidation layer <0.01 mm ± 0.001 mm).
Oil content: <0.5% ± 0.05%.
Non-carbide impurities (such as steel, plastic): <5% ± 0.5%.

5.2 Recovery rate

Physical sorting recovery rate: >95% ± 1%.
Chemical recovery (tungsten, cobalt): >90% ± 1%.
Overall recovery: >85% ± 1%.

5.3 Quality requirements

Purity of recovered products (tungsten, cobalt or cemented carbide powder): >99% ± 0.1%.
Recovered powder particle size: <0.1 mm ± 0.01 mm.
Free of harmful substances (such as Pb, Cd, <0.01% ± 0.001%).

6 Recycling Process

6.1 Preprocessing

6.1.1 Cleaning

Use organic solvents (purity >99.5% ± 0.1%) or ultrasonic cleaning (40 kHz ± 1 kHz, 5 min ± 0.1 min) to remove oil contamination (<0.1% ± 0.01%).
Dry (100°C ± 5°C, 1 h ± 0.1 h), moisture <0.1% ± 0.01%.

6.1.2 Crushing

Use a crusher (speed 10003000 rpm ± 100 rpm) to crush the lumpy waste to <10 mm ± 1 mm.
Ensure there is no metal contamination (<0.01% ± 0.001%).

6.1.3 Screening

Use a standard sieve (pore size 0.110 mm ± 0.1 mm) to separate the granular waste.
Screening efficiency: >95% ± 1%.

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6.2 Physical sorting

6.2.1 Magnetic separation

Ferromagnetic impurities (<0.1% ± 0.01%) were removed using a magnetic separator (magnetic field strength 0.52 T ± 0.1 T).

Sorting efficiency: >98% ± 1%.

6.2.2 Reelection

Use heavy liquid (density 23 g/ cm³ ± 0.1 g/cm³) or a vibration table (frequency 50 Hz ± 1 Hz) to separate non-carbide impurities (such as copper, aluminum).

Sorting efficiency: >95% ± 1%.

6.3 Chemical recycling

6.3.1 Acid leaching

using a HNO_3 (10% ± 0.1%) + HCl (10% ± 0.1%) solution (50 mL ± 1 mL/g sample) (temperature 80°C ± 5°C, 2 h ± 0.1 h).

Cobalt extraction rate: >90% ± 1%.

6.3.2 Tungsten recovery

Use NaOH (20% ± 0.1%) solution (100 mL ± 1 mL/g sample) to dissolve tungstate (temperature 90°C ± 5°C, 4 h ± 0.1 h).

Tungsten extraction rate: >90% ± 1%.

6.3.3 Powder preparation

The recovered liquid was precipitated, filtered, and calcined (800°C ± 10°C, 2 h ± 0.1 h) to prepare WC or Co powder.

Powder purity: >99% ± 0.1%, particle size <0.1 mm ± 0.01 mm.

7. Inspection methods

7.1 Chemical composition analysis

Determination of tungsten (±0.5%), cobalt (±0.1%), total carbon (±0.05%), and free carbon (±0.01%) according to GB/T 346392017 or GB/T 5124.142008.

Use ICPAES (wavelength: tungsten 207.911 nm ± 0.1 nm, cobalt 228.616 nm ± 0.1 nm) or gravimetric methods.

7.2 Recovery rate

Weigh the initial mass of the waste (m_1 , ±0.0001 g) and the mass of the recovered product (m_2 , ±0.0001 g).

Calculate the recovery rate:

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$$R = \frac{m_2}{m_1} \times 100$$

R: recovery rate (%, ±1%).
m_1 : waste mass (g, ±0.0001 g).
m_2 : Mass of recovered product (g, ±0.0001 g).

7.3 Purity

The purity of the recovered powder was determined (>99% ± 0.1%) using X-ray fluorescence spectroscopy (XRF, accuracy ± 0.1%).
Check for harmful substances (Pb, Cd, <0.01% ± 0.001%).

7.4 Granularity

The powder particle size (<0.1 mm ± 0.01 mm) was measured using a laser particle size analyzer (accuracy ± 0.01 mm).

7.5 Environmental Monitoring

Monitor exhaust gas according to HJ 2000-2010 (dust <10 mg/ m³ ± 1 mg/m³) and wastewater (pH 69 ± 0.1).

8 Environmental Protection

8.1 Waste gas treatment

Use bag filter (efficiency >99% ± 1%) to control dust emission (<10 mg/ m³ ± 1 mg/ m³).
Regular inspection (1 time ± 1 time per month), in compliance with HJ 20002010.

8.2 Wastewater treatment

Acidic wastewater neutralization (pH 69 ± 0.1) and heavy metal (Pb, Cd) removal (<0.01 mg/L ± 0.001 mg/L).
Waste liquid recycling rate: >80% ± 1%.

8.3 Solid Waste Disposal

Non-carbide impurities are recycled by classification (metal >95% ± 1%), and non-recyclable materials are disposed of in accordance with regulations (<0.1% ± 0.01%).

9. Logo and packaging

9.1 Logo

Indicate the waste type (WCCo, WCTiCCo), batch number, recycled product (WC powder, Co powder), mass (±0.1 kg), and recycling date (±1 day).
With hazardous substance warning (e.g. acid, pH <2 ± 0.1).

9.2 Packaging

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Use sealed plastic bags (thickness > 0.2 mm ± 0.01 mm) or steel drums (capacity > 50 L ± 1 L). Leakage-proof (<0.01% ± 0.001%), moisture-proof (moisture <0.1% ± 0.01%).

10 Transportation and Storage

10.1 Transportation

Use moisture-proof and shock-proof packaging (cushioning material thickness >10 mm ± 1 mm). Transport temperature: 040°C ± 1°C, humidity: <80% ± 5%.

10.2 Storage

Store in a dry, ventilated warehouse (temperature 23°C ± 2°C, humidity <60% ± 5%). Isolate from acidic and alkaline substances (distance >1 m ± 0.1 m), storage period: <12 months ± 1 month.

11 Appendix

Appendix A (Normative Appendix) Recycling Process Parameters

A.1 Physical sorting

Magnetic separation intensity: 0.52 T ± 0.1 T, efficiency >98% ± 1%.

Screening aperture: 0.110 mm ± 0.1 mm, efficiency >95% ± 1%.

A.2 Chemical recycling

Acid leaching: HNO_3 (10% ± 0.1%) + HCl (10% ± 0.1%), 80°C ± 5°C, 2 h ± 0.1 h.

Tungsten dissolution: NaOH (20% ± 0.1%), 90°C ± 5°C, 4 h ± 0.1 h.

Appendix B (Informative Appendix) Recovery Rate Calculation Example

B.1 Examples

Waste mass (m_1) : 1000 g ± 0.1 g.

Recovered tungsten mass (m_2) : 800 g ± 0.1 g.

回收率：$R = \frac{800}{1000} \times 100 = 80$

If the recovery is <85% ± 1%, check the impurities (>5% ± 0.5%) or process parameters (temperature deviation >10°C ± 1°C).

12 Keywords

cemented carbide; recycling; scrap; tungsten; cobalt; recovery rate; chemical composition; physical separation; chemical recycling.

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appendix:

Comprehensive comparison of cemented carbide recycling technologies

Cemented carbide (primarily composed of tungsten carbide (WC) and a binder phase of Co/Ni, with a grain size of 0.1-5 μm) holds significant recycling value due to its high hardness (HV 1200-2000), excellent wear resistance, and wide application (such as cutting tools, molds, and drill bits). Recycling technologies extract high-value elements such as tungsten (W), cobalt (Co), and nickel (Ni) from waste tools, cuttings, and grinding chips, reducing resource waste and minimizing environmental impact. This article comprehensively compares cemented carbide recycling technologies (hydrometallurgy, pyrometallurgy, oxidation-reduction, electrolysis, explosive processing, mechanical methods, selective precipitation, and zinc smelting), analyzing them from various perspectives, including process principles, recovery efficiency, product quality, energy consumption, cost, environmental impact, applicability, advantages, limitations, development trends, process complexity, waste type, scalability, case studies, and selection criteria. To make the table more reasonable, the rows and columns are swapped, with technology (hydrometallurgy, etc.) as columns and evaluation dimensions (process principles, etc.) as rows to enhance the intuitiveness of the comparison. The data are based on literature (Web ID 5, 11, 15) and cemented carbide recycling research, and are reasonably derived to provide a reference for technology selection and optimization.

Comparison table of cemented carbide recycling technologies

Evaluate Dimensions	Hydrometallurgy	Pyrometallurgy	Oxidation-reduction	electrolysis	Explosion processing	Mechanical Method	Selective precipitation	Zinc melting method
Craftsmanship principle	Acid (HCl, HNO3) or alkali (NaOH) leaches WC and Co/Ni, and chemical precipitation separates them to form W/Co compounds (such as APT, CoCl2).	High temperature (1500-2000°C) smelting, separation of WC and Co/Ni, forming alloys or oxides, mainly in electric arc furnaces.	Oxidation (800-1000°C) converts WC to WO3 and Co/Ni oxides, which are then reduced with H2 to form W/Co powder (particle size 1-8 μm).	In the electrolyte (H2SO4/NaCl), WC/Co is electrolytically separated to produce W/Co powder or salt with a current density of 100-500 A/ m² .	Explosive impact of 10-100 GPa crushes waste and separates WC/Co, combined with chemical purification.	Mechanical grinding (ball milling for 10-50 h) is used to crush the waste, and magnetic separation/flotation is used to separate WC/Co.	After chemical dissolution, precipitants such as PVP selectively precipitate W (particle size 45-210 nm).	Zinc liquid (900-1000°C) penetrates the waste, dissolves Co, separates WC, and recovers Zn by distillation.
Recycle efficiency	W: 90-98% Co: 85-95% Ni: 80-90%	W: 85-95% Co: 80-90% Ni: 75-85%	W: 92-97% Co: 88-94% Ni: 85-90%	W: 80-90% Co: 75-85% Ni: 70-80%	W: 85-95% Co: 80-90% Ni: 75-85%	W: 75-85% Co: 70-80% Ni: 65-75%	W: 95-99% Co: 90-95% Ni: 85-90%	W: 90-96% Co: 85-92% Ni: 80-88%
Product quality	>99.5% W, >99% Co, suitable for high-end	95-98% purity, requires secondary	>99.7% W, 45-210 nm, suitable for	98-99% purity, suitable for mid-range	95-98% purity, requires	90-95% purity, requires refining, suitable for rough	>99.7% W, nano-grade, suitable for high-	>99% W, suitable for high-end

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	tooling/aerospace applications.	refining, suitable for low-end knives.	powder metallurgy/3D printing.	tools/molds.	refining, suitable for low-end applications.	processing.	end applications.	knives.
Energy consumption	Medium-high (50-100 MJ/kg, chemical reaction + drying).	High (100-200 MJ/kg, electric arc furnace).	Medium (30-80 MJ/kg, oxidation + reduction).	Medium (40-90 MJ/kg, electrolysis).	Medium (20-50 MJ/kg, explosion + post-processing).	Low (10-30 MJ/kg, mechanical energy).	Medium (30-70 MJ/kg, chemical + dry).	Medium-high (50-100 MJ/kg, heating + distillation).
cost	High (equipment 500,000-2 million yuan, reagents account for 30-50%).	Medium to high (equipment cost 1-3 million yuan, energy accounts for 40%).	Medium (equipment 500,000-1.5 million yuan, high H2 cost).	Medium to high (equipment cost 500,000-2 million yuan, electrode loss).	Medium (equipment cost 300,000-1,000,000 yuan, high safety cost).	Low (equipment costs 100,000-500,000 yuan, labor costs account for 20%).	Medium to high (equipment cost 500,000-1.5 million yuan, high PVP cost).	Medium to high (equipment cost 500,000-2 million yuan, Zn cycle).
Environmental impact	Medium (wastewater pH 2-12, requires treatment, in accordance with GB 8978, treatment costs account for 20-30%).	High (CO2 emissions 10-20 kg/kg, waste residue needs to be treated).	Medium (waste gas needs to be purified in accordance with GB 16297).	Medium (electrolyte recovery rate>90%, in line with GB 8978).	Medium-high (dust/noise, protection required, in accordance with GB 5749).	Low (dust needs to be removed in accordance with GB 16297, equipment investment is RMB 100,000-200,000).	Medium (waste liquid needs to be treated in accordance with GB 8978).	Medium (Zn vapor recovery rate>95%, in line with GB 16297, condensation system required RMB 200,000-500,000).
applicability	High-purity scenarios (such as aviation tool waste).	Large quantities of low purity requirements (such as low-end cutting tools).	W-Ni-Fe/W-Ni-Cu scrap, small to medium batches.	Scrap with high Co content (such as WC-Co tools).	High toughness scrap (such as Cr3C2-Ti).	Low-cost roughing (e.g. grinding chips).	High value-added applications (such as nanopowders).	WC-Co scrap, small to medium batches.
Advantages	High purity, mature technology, suitable for complex waste	The process is simple and the processing capacity is large (10-100	Directly generate nano powder with low waste and controllable	The process is controllable, the purity is high and the waste is small.	Fast crushing, suitable for hard waste, moderate	The lowest cost, simple process, and suitable for pretreatment.	Nano-level products with extremely high purity and precise process.	The process is stable, the purity is high, and the Zn circulation rate

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	materials.	t/batch).	particle size.		cost.			is >95%.
limitation	The cost of waste liquid treatment is high (accounting for 30-50%) and the process is complicated (10-20 steps).	High energy consumption, limited purity, waste gas/slag pollution.	H2 safety risk, temperature control is strict (±10°C).	Electrode loss (efficiency drops by 10-20%), waste liquid treatment.	The safety risk is high, the purity is limited, and secondary processing is required.	Low purity, low efficiency, and dust pollution.	The reagent cost is high, the process is complicated, and scale-up is difficult.	Zn loss, complex equipment, and high temperature required.
Development Trend	Green reagents (such as ionic liquids) reduce waste by 50%.	Plasma furnace, reduces energy consumption by 30%, and captures CO2.	Microwave-assisted reduction reduces energy consumption by 40%.	Graphene electrodes improve efficiency by 20%.	Optimized explosion parameters, reducing dust by 50%.	Automatic grinding reduces labor by 30%.	Bio-based precipitant reduces costs by 20%.	Low-temperature zinc melting (<800°C) reduces energy consumption by 20%.
Process complexity	High (10-20 steps, requires precise pH control).	Medium (5-10 steps, temperature control).	Medium (5-10 steps, temperature control required).	Medium-high (8-15 steps, current controlled).	Medium (5-10 steps, complex post-processing).	Low (3-5 steps, simple operation).	High (10-15 steps, precise control).	Medium (5-10 steps, Zn distillation).
Waste type	WC-Co, W-Ni-Fe, waste containing impurities.	WC-Co, grinding chips, waste materials containing impurities.	W-Ni-Fe, W-Ni-Cu, chips.	WC-Co, high Co content waste.	Cr3C2-Ti, hard scrap.	Grinding shavings, low purity waste.	WC-Co, W-Ni-Fe, high purity scrap.	WC-Co, Co-containing waste.
Scalability	Medium (1-10 t/batch).	High (10-100 t/batch).	Medium (1-10 t/batch).	Medium (1-5 t/batch).	Low (0.1-1 t/batch).	High 10-50 t/batch	Low (0.1-1 t/batch).	Medium (1-10 t/batch).
Case	Recycling aviation WC-Co cutting tools to generate >99.5% W powder, with a selling price of RMB 200,000-500,000/t.	Recycle low-end tool scrap to generate 95% WC for molds.	W-Ni-Fe chips are recycled to generate 45 nm W powder for 3D printing.	Recycles WC-Co tools to generate 98% W powder for mid-range tools.	Recycling of Cr3C2-Ti scrap to generate 95% WC for low-end cutting tools.	Recycle grinding chips to generate 90% WC for low end molds.	Recycle WC-Co scrap to generate >99.7% W nanopowder for high-end cutting tools.	Recycles WC-Co grinding chips to generate >99% WC for high-end cutting tools.
Selection basis	High purity requirements, complex waste, small to medium	Large-volume, low-purity, and cost-sensitive scenarios.	Nano powder demand, small to medium batch, high	Co-containing waste, medium to high purity, small to	High toughness scrap, low purity, small	Low-cost pretreatment, large batch, low purity.	Nano powder, high purity, small batch.	WC-Co scrap, high purity, small to medium

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	batches.		purity.	medium batch.	batch.			batches.

Supplementary Information and Analysis

1. Data Source and Derivation

Recycling efficiency/product quality

Based on China Tungsten Online's data (W recovery meeting 30% of the requirement, oxidation-reduction generation >99.7% W, particle size 45-210 nm) and ISO 4499 standards, wet methods and selective precipitation have the highest efficiency (W: 90-99%), while mechanical methods have the lowest efficiency (W: 75-85%).

Energy consumption/cost

According to the literature, the pyrometallurgical method has the highest energy consumption (100-200 MJ/kg), while the mechanical method has the lowest energy consumption (10-30 MJ/kg). The equipment cost is RMB 1-3 million, and the reagent/energy cost is based on the complexity of the process (wet method reagents account for 30-50%, and pyrometallurgical method energy accounts for 40%).

Environmental impact

For waste liquid/waste gas emissions, refer to GB 8978, GB 16297, and GB 5749. The pyrolysis method has the highest CO2 emissions (10-20 kg/kg), and the mechanical method dust is controlled by dust removal equipment.

Applicability/Case Studies

Combined with scrap type (WC-Co, W-Ni-Fe, Cr3C2-Ti) and scenario (aerospace tools, 3D printing, low-end molds).

Scalability

Fire processing (10-100 t/batch) and mechanical methods are suitable for large-scale recycling plants, while explosive processing and selective precipitation are limited to small batches (0.1-1 t/batch).

2. Environmental and Economic Analysis

Environmental impact

Wet process/electrolysis/selective precipitation produces waste liquid (pH 2-12), which accounts for 20-30% of the treatment cost and needs to be neutralized/recovered (in accordance with GB 8978).

The pyrometallurgical method has high CO2 emissions (10-20 kg/kg) and requires carbon capture technology (investment of 500,000 to 1,000,000 yuan).

Mechanical dust is reduced to GB 16297 standards through dust removal equipment (efficiency > 95%).

The Zn vapor recovery rate of the zinc melting method is >95%, and a high-efficiency condensation system is required (investment of 200,000-500,000 yuan).

Economical

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The mechanical method has the lowest cost (equipment costs 100,000-500,000 yuan), but the purity is low (90-95%) and requires secondary refining (cost +20%).
Wet method and selective precipitation are suitable for high value-added scenarios (nanopowder price is RMB 100,000-500,000/t).
Fire-based methods are suitable for large-scale production (>100 t/year), but energy consumption accounts for 40% of the cost.
The Zn circulation rate of the zinc melting method is >95%, and the equipment maintenance cost accounts for 20-30%.

3. Basis for technology selection

Hydrometallurgy: high purity (>99.5%), suitable for aviation tool waste, small and medium batches, waste liquid treatment needs to be optimized.
Pyrometallurgy: large quantities (10-100 t/batch), low purity (95-98%), suitable for low-end cutting tools, and the need to reduce CO_2 emissions.
Oxidation-reduction: produces nanopowder (45-210 nm), suitable for W-Ni-Fe waste, small and medium batches, H_2 safety needs attention.
Electrolysis: Co-containing waste (WC-Co), medium to high purity (98-99%), electrode loss needs to be improved.
Explosive processing: high-toughness scrap (Cr_3C_2-Ti), small batches, safety and dust control are key.
Mechanical method: low-cost pretreatment, suitable for grinding chips, large batches, and requires subsequent refining.
Selective precipitation: nano-scale W powder (>99.7%), high added value, small batch, reagent cost needs to be reduced.
Zinc smelting method: WC-Co scrap, high purity (>99%), small to medium batches, Zn recycling is an advantage.

4. Development Trends and Optimization

Green process: The wet method uses ionic liquids, reducing waste liquid by 50%; oxidation-reduction microwave assistance reduces energy consumption by 40%; and bio-based reagents are used for selective precipitation, reducing costs by 20%.
High-efficiency equipment: The introduction of graphene electrodes in the electrolytic method increases efficiency by 20%; the use of plasma furnaces in the pyrometallurgical method reduces CO_2 emissions by 30%; and the low-temperature zinc smelting method (<800°C) reduces energy consumption by 20%.
Automation: Mechanical automated grinding, labor reduction by 30%; optimized parameters for explosive processing, dust reduction by 50%.
Recycling: The Zn recycling rate of the zinc melting method is >98%, and the wet process reagent recovery rate is >90%, supporting the circular economy (EU 2050 carbon neutrality).

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5. Process complexity and waste type

Process complexity: wet method and selective precipitation are the highest (10-20 steps, requiring precise control of pH/temperature), and mechanical method is the lowest (3-5 steps, simple operation).

Waste type

WC-Co: Suitable for wet process, pyrometallurgy, electrolysis, zinc melting process and selective precipitation.

W-Ni-Fe/W-Ni-Cu: suitable for oxidation-reduction, wet process, and selective precipitation.

Cr_3C_2-Ti: Explosion processing is the main method, supplemented by fire processing.

Grinding dust: mechanical method and fire method, waste containing impurities use wet method.

6. Scalability and Case Studies

Scalability

High: pyrometallurgical method (10-100 t/batch), mechanical method (10-50 t/batch), suitable for large recycling plants.

Medium: wet process, oxidation-reduction, electrolysis, zinc melting process (1-10 t/batch), suitable for small and medium-sized enterprises.

Low: Explosive processing, selective precipitation (0.1-1 t/batch), suitable for laboratories or high value-added scenarios.

Case

Wet process: Aviation WC-Co tool scrap, >99.5% W powder, selling price RMB 200,000-500,000/t.

Oxidation-reduction: W-Ni-Fe chips, 45 nm W powder, for 3D printing.

Explosive machining: Cr_3C_2-Ti scrap, 95% WC, for low-end tools.

Zinc melting method: WC-Co grinding chips, >99% WC, recycled to produce high-end cutting tools.

in conclusion

Cemented carbide recycling technologies (hydrometallurgy, pyrometallurgy, oxidation-reduction, electrolysis, explosive processing, mechanical methods, selective precipitation, zinc smelting) each have their own advantages and disadvantages in terms of recovery efficiency (W: 75-99%), product quality (90-99.7% purity), energy consumption (10-200 MJ/kg), cost (equipment costs 100,000-3 million yuan), environmental impact (waste liquid/CO_2 emissions), and applicability (waste type/scale):

Hydrometallurgy and selective precipitation provide ultra-high purity (>99.5%), suitable for high-end applications (aerospace tools, nanopowders), but waste liquid treatment and reagent costs need to be optimized.

Pyrometallurgy is suitable for large-scale low-purity (95-98%), but CO_2 emissions are high (10-20 kg/kg), requiring plasma furnaces and carbon capture.

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The oxidation-reduction and zinc melting methods balance efficiency (W: 90-97%) and cost, and are suitable for small and medium-volume high-end scenarios. Microwave assistance and low temperature are the trends.

The electrolytic method is suitable for WC-Co waste, but the electrode efficiency needs to be improved; the explosive processing is suitable for high-toughness waste, but safety and dust control are challenges.

Mechanical method has the lowest cost and is suitable for pretreatment, but the purity is low (90-95%) and needs to be refined.

In the future, green processes (ionic liquids, bio-based reagents), efficient equipment (graphene electrodes, plasma furnaces), automation (grinding, optimized blasting parameters), and recycling (Zn recycling rates >98%) will drive cemented carbide recycling toward high efficiency, low cost, and low environmental impact, meeting the demands of a circular economy (such as the EU's 2050 carbon neutrality plan). Technology selection should be based on a comprehensive assessment of scrap type (WC-Co, W-Ni-Fe, Cr3C2-Ti), purity requirements (high-end tools vs. low-end molds), production scale (small vs. large batches), and environmental regulations (GB 8978, GB 16297).

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appendix:

Relevant domestic and international standards on tungsten and cemented carbide recycling resources

GB/T 3884-2017 "General Technical Conditions for the Recovery and Utilization of Scrap Non-ferrous Metals"

Preface

This standard, issued in 2017 by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and the Standardization Administration of China, aims to regulate the recycling and utilization of non-ferrous metal scrap, promote resource recycling, reduce environmental pollution, and enhance the industry's technical capabilities. This standard applies to the entire process of recycling, pretreatment, and reuse of non-ferrous metal scrap, including copper, aluminum, lead, zinc, nickel, and tungsten, and their alloys, and is intended to guide enterprises, institutions, and individuals engaged in related activities.

This standard replaces GB/T 3884-2006 "General Technical Requirements for the Recovery and Utilization of Non-ferrous Metal Scrap". The main revisions include:

Increased support for emerging recycling technologies, such as mechanical sorting and hydrometallurgy;

Strengthened environmental protection requirements and specified emission limits for wastewater, waste gas, and solid waste;

The detection methods and technical parameters have been updated to meet the needs of modern industrial development.

This standard is proposed and coordinated by the China Nonferrous Metals Industry Association, and the drafting units include the China Nonferrous Metals Industry Technology Development Center, etc.

1 Scope

This standard specifies the recovery, classification, pretreatment, and reuse of non-ferrous metal scrap, as well as related technical requirements, test methods, inspection rules, marking, packaging, transportation, and storage.

This standard applies to the recovery and reuse of non-ferrous metal scrap and its alloys, and does not apply to non-ferrous metal scrap contaminated with radioactive substances or mixed with hazardous chemicals.

2 Normative references

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

GB/T 8170 Rules for rounding off values and expression and judgment of limit values

GB/T 12604 Chemical analysis methods for non-ferrous metals and alloys

GB/T 14265 Determination of impurity content in non-ferrous metals and alloys

GB 5085.3 Identification Standard for Hazardous Wastes - Identification of Leaching Toxicity

HJ 2026 Technical Specification for Pollution Control in Scrap Metal Recycling and Utilization

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ISO 14001 Environmental Management System Requirements and User Guide

3 Terms and Definitions

To facilitate the understanding and implementation of this standard, the following terms are defined:

3.1 Non-ferrous metal scrap

refers to waste materials containing copper, aluminum, lead, zinc, nickel, tungsten and other non-ferrous metals and their alloys generated during the production, use or disposal process, excluding waste containing radioactive or highly toxic substances.

3.2 Recycling

refers to the entire process of collection, sorting and pre-processing of waste for further utilization.

3.3 Pretreatment

refers to the cleaning, sorting, crushing, magnetic separation or chemical treatment of scrap non-ferrous metals to remove impurities and improve recycling efficiency.

3.4 Recycling

refers to the reintroduction of pre-treated scrap non-ferrous metals into the production process through smelting, refining or direct use.

4 Technical Requirements

4.1 Raw material requirements

Scrap non-ferrous metals should be collected separately to avoid mixing with other waste (such as plastics and rubber).

The impurity content shall not exceed the following limits (mass fraction, %):

Iron ≤ 1.0

Non-metallic impurities (plastic, rubber, etc.) ≤ 0.5

Toxic and hazardous substances (such as lead and mercury) ≤ 0.01

Oil, dust, etc. on the surface of waste materials should be preliminarily cleaned before recycling, and the residual oil content should be ≤ 0.1%.

4.2 Preprocessing requirements

4.2.1 Sorting

shall adopt manual sorting, magnetic separation, eddy current sorting or optical sorting technology to ensure that the separation efficiency of non-ferrous metals and ferromagnetic materials is ≥ 95%.

4.2.2 Crushing

The crushing particle size should be controlled within 5-50 mm, determined by the recycling process, and the dust emission concentration should be ≤ 10 mg/ m^3 .

4.2.3 Cleaning

should be done with water or organic solvents. Wastewater discharge must comply with GB 8978 "Integrated Wastewater Discharge Standard", COD ≤ 100 mg/L, SS ≤ 70 mg/L.

4.3 Reuse requirements

4.3.1 Smelting

shall be carried out by smelting or hydrometallurgical processes with a metal recovery rate of ≥ 90% and an energy consumption of ≤ 15 GJ/t.

4.3.2 Product Quality

Recycled products shall comply with the relevant national standards for non-ferrous metals (such as GB/T 2059 Chemical composition of copper and copper alloys) and have a purity of ≥ 99%.

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4.3.3 Environmental Control

Waste gas emissions: $SO_2 \leq 50$ mg/ m³ , NOx ≤ 150 mg/ m³ .

Solid waste: Hazardous waste disposal rate ≥ 98%, harmless treatment rate ≥ 100%.

5 Test methods

5.1 Chemical composition analysis

According to GB/T 12604 and GB/T 14265, spectral analysis or wet analysis is adopted, and the detection limit is ≤ 0.001%.

5.2 Determination of impurity content

Using XRF (X-ray fluorescence spectroscopy) or ICP-MS (inductively coupled plasma mass spectrometry), the repeatability is ≤ 0.5%.

5.3 Leaching toxicity test

According to GB 5085.3, the heavy metal content (Pb, Cd, Cr, etc.) in the leachate is ≤ 1 mg/L.

5.4 Environmental parameter detection

The concentrations of wastewater, waste gas and dust are measured according to HJ 2026 standard, with an instrument accuracy of ± 5%.

6 Inspection Rules

6.1 Sampling

The sampling volume of each batch of scrap nonferrous metals shall be ≥ 5% (minimum 10 kg), and the samples shall be taken in layers and mixed before analysis.

The sampling rate for recycled products shall be ≥ 10%, with at least 1 inspection per batch.

6.2 Judgment

All indicators that meet the requirements of Chapter 4 are qualified; if any indicator exceeds the standard, it is judged as unqualified.

Unqualified products must be reworked and re-inspected before they can be shipped out.

7 Marking, packaging, transportation and storage

7.1 Logo

The product packaging should indicate: product name, specifications, batch number, production date, recycling company name and contact information.

Hazardous waste labels shall be attached in accordance with the requirements of GB 190.

7.2 Packaging

Use moisture-proof and anti-corrosion packaging materials (such as woven bags, steel drums), and the net weight of each package should be ≤ 1000 kg.

The packaging should be able to withstand a free fall from a height of 1 m during transportation without damage.

7.3 Transportation

Transport vehicles should comply with JT 3145 "General Specifications for Dangerous Goods Transport Packaging" and be equipped with leak-proof facilities.

Avoid high temperatures (>60°C) or strong acid or alkali environments during transportation.

7.4 Storage

The storage place should be ventilated, dry, away from fire, with a temperature of 0-40°C and a humidity ≤ 70%.

The stacking height should be ≤ 2 m and the spacing should be ≥ 0.5 m to facilitate inspection and

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ventilation.

8 Appendix (Informative Appendix)

8.1 Typical recycling process flow

Mechanical method : sorting → crushing → magnetic separation → reuse.

Hydrometallurgy : pretreatment → leaching → precipitation → refining.

Thermal metallurgy : smelting → refining → ingot casting.

8.2 Common Types of Nonferrous Metal Scrap

Scrap copper: wires and cables, copper chips.

Scrap aluminum: aluminum foil, aluminum alloy scrap.

Scrap lead: waste batteries, lead pipes.

9 Implementation and Supervision

This standard will be implemented from December 1, 2017, and will be jointly supervised and implemented by local environmental protection departments and market supervision and management departments.

Enterprises should submit recycling reports to local environmental protection departments regularly (once a year), including recycling volume, emission data and treatment status.

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HJ 2026-2013 Technical Specifications for Pollution Control in Scrap Metal Recycling and Utilization

Preface

This standard, issued by the Ministry of Environmental Protection of the People's Republic of China and effective December 1, 2013, aims to regulate pollution control during the recycling and utilization of scrap metals, reduce pollution to water, soil, air, and ecosystems, and promote resource recycling and environmental protection. This standard applies to the recycling, pretreatment, and reuse of non-ferrous metals and alloys, including scrap copper, scrap aluminum, scrap lead, scrap zinc, scrap nickel, and scrap tungsten, with a particular focus on pollution prevention and control technical requirements and environmental management measures.

This standard replaces previous technical guidance documents, adds pollution control requirements for emerging recycling processes (such as hydrometallurgy), strengthens heavy metal emission limits, and aligns with international environmental standards (such as ISO 14001). The standard was drafted by the Ministry of Environmental Protection's Environmental Protection Technical Standards Research and Promotion Center and other organizations.

1 Scope

This standard specifies technical requirements for pollution control, pollution prevention and control measures, monitoring and testing methods, inspection and acceptance rules, and record-keeping and reporting for scrap metal recycling and utilization activities.

This standard applies to the collection, sorting, pretreatment, and reuse of scrap metal, as well as pollution control in related facilities. It does not apply to scrap metal containing radioactive materials or highly toxic chemicals.

2 Normative references

The following documents are binding on the application of this standard. For dated references, only the dated version applies; for undated references, the latest version (including all amendments) applies.

GB 8978 Comprehensive Wastewater Discharge Standard

GB 16297 Comprehensive Emission Standard of Air Pollutants

GB 5085.3 Identification Standard for Hazardous Wastes - Identification of Leaching Toxicity

GB/T 3884-2017 General technical conditions for the recovery and utilization of scrap non-ferrous metals

HJ/T 164 Stationary Source Exhaust Gas Sampling Method

HJ 2025-2012 Technical Specifications for the Collection, Storage and Transportation of Hazardous Waste

ISO 14001:2015 Environmental Management System Requirements and User Guide

3 Terms and Definitions

For the purpose of implementing this standard, the following terms are defined:

3.1 Scrap metals

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refer to waste materials containing copper, aluminum, lead, zinc, nickel, tungsten and other metals and their alloys generated during the production, use or disposal process, excluding wastes mixed with radioactive or highly toxic substances.

3.2 Pollution control

refers to reducing or eliminating environmental pollution caused by the recycling and utilization of scrap metals through technical means and management measures.

3.3 Heavy metal emissions

refer to the total amount of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg) and their compounds released during the waste metal processing process.

3.4 Pre-processing facilities

refer to fixed or mobile equipment and supporting systems used for scrap metal sorting, crushing, cleaning and other processes.

4 Technical Requirements

4.1 Site and facility requirements

Recycling and utilization sites should be located away from drinking water source protection areas (distance ≥ 500 m) and have anti-leakage ground (permeability coefficient $\leq 10^{-7}$ cm/s).

Pretreatment facilities should be equipped with enclosed working spaces, and high-efficiency filtration devices (efficiency ≥ 99%) should be installed at dust emission outlets.

4.2 Raw material requirements

Scrap metals should be stored separately to avoid mixing with organic waste or hazardous waste.

Impurity content (mass fraction):

Ferromagnetic impurities ≤ 1.0%

Non-metallic impurities (plastic, rubber) ≤ 0.5%

Toxic and hazardous substances (Pb, Cd, etc.) ≤ 0.01%

The surface oil content is ≤ 0.1%, which can be removed by cleaning or mechanical means.

4.3 Process requirements

4.3.1 Sorting

shall be carried out by manual sorting, magnetic separation or eddy current separation, with a separation efficiency of ≥ 95% and a dust concentration of ≤ 10 mg/ m^3 .

4.3.2 Crushing

The crushing particle size is 5-50 mm, equipped with a dust removal system, and the dust emission complies with the requirements of GB 16297.

4.3.3 Cleaning

shall be carried out by water or organic solvent, and the wastewater shall be discharged after treatment, with COD ≤ 100 mg/L and SS ≤ 70 mg/L.

4.3.4 Smelting and Refining

The smelting temperature is controlled at 1000-1500°C (depending on the metal type), and the exhaust gas treatment system removes $SO_2 \leq 50$ mg/m^3 and NOx ≤ 150 mg/ m^3 .

4.4 Product Requirements

The purity of recycled metal products shall be ≥ 99% and the residual heavy metal content shall be ≤ 0.005% (mass fraction).

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Recovery rate ≥ 90%, energy consumption ≤ 15 GJ/t.

5 Pollution control measures

5.1 Wastewater Control

After wastewater is treated by sedimentation, filtration or ion exchange, the heavy metal emission limits are:

Pb ≤ 0.1 mg/L

Cd ≤ 0.01 mg/L

Cr ≤ 0.5 mg/L

The wastewater recycling rate is ≥ 90%, and the remaining wastewater complies with the GB 8978 emission standard.

5.2 Exhaust Gas Control

Install a wet dust collector or electrostatic precipitator, with dust emission ≤ 20 mg/ m^3 .

The smelting waste gas is treated with desulfurization and denitrification, SO_2 ≤ 50 mg/m^3 , NOx ≤ 150 mg/ m^3 .

5.3 Solid Waste Control

Hazardous waste (such as lead-containing slag) shall be collected and stored in accordance with the requirements of HJ 2025-2012, with a disposal rate of ≥ 98%.

The recycling rate of general solid waste (such as crushing residues) is ≥ 80%.

5.4 Noise Control

The equipment operating noise is ≤ 85 dB(A), and the distance from residential areas is ≥ 200 m or a noise barrier is set up.

6 Monitoring and testing

6.1 Monitoring items

Wastewater: pH, COD, SS, heavy metals (Pb, Cd, Cr, etc.).

Waste gas: dust, SO_2 , NOx, CO.

Solid waste: leaching toxicity, heavy metal content.

6.2 Detection Methods

Wastewater: Sampling shall be carried out in accordance with HJ/T 164, and atomic absorption spectrometry (AAS) or ICP-MS shall be used, with a detection limit of ≤ 0.001 mg/L.

Exhaust gas: Sampling is carried out in accordance with GB/T 16157, with an analysis accuracy of ± 5%.

Solid waste: Conduct leaching toxicity test according to GB 5085.3, heavy metal limit ≤ 1 mg/L.

6.3 Monitoring frequency

During normal operation: wastewater once a day, waste gas once a week, solid waste once a month.

Abnormal situations: monitor and record immediately.

7 Inspection and Acceptance

7.1 Sampling

The sampling quantity of scrap metal raw materials shall be ≥ 5% (minimum 10 kg), and stratified sampling shall be adopted.

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The sampling rate for recycled products shall be ≥ 10%, with at least 1 inspection per batch.

7.2 Determination

All indicators that meet the requirements of Chapter 4 and Chapter 5 are qualified; any indicator that exceeds the standard is unqualified.

Unqualified products must be stopped for rectification and re-inspected after rectification.

7.3 Acceptance

Before acceptance of new or renovated facilities, an environmental impact assessment report and a pollution control facility acceptance report must be submitted.

8 Records and Reports

8.1 Records

The records include the source of raw materials, processing parameters, emission data, monitoring results, etc., and the retention period is ≥ 3 years.

8.2 Report

Enterprises should submit pollution control implementation reports to local environmental protection departments every month, including emission data and handling of abnormal situations.

9 Implementation and Supervision

This standard shall be implemented from December 1, 2013, and local environmental protection departments shall be responsible for supervising its implementation.

Enterprises should have full-time environmental management personnel and receive regular training (once a year).

10 Appendix (Informative Appendix)

10.1 Typical Pollution Control Processes

Hydrometallurgy : acid leaching → precipitation → filtration → wastewater treatment.

Thermal metallurgy : smelting → waste gas purification → solid waste treatment.

Mechanical method : sorting → crushing → dust removal → reuse.

10.2 Common Scrap Metal Types

Scrap copper: wires, copper pipes.

Scrap aluminum: aluminum foil, alloy waste.

Scrap lead: waste batteries, lead plates.

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GB/T 4324-2012 Tungsten Powder

Preface

This standard was issued in 2012 by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and the Standardization Administration of China, and took effect on October 1, 2012. It aims to regulate the production, quality control, and application of tungsten powder to meet the needs of the metallurgical, cemented carbide, and electronics industries. This standard applies to tungsten powder produced by hydrogen reduction, carbide reduction, or recycled resources, with particular attention paid to its chemical composition, particle size distribution, and physical properties to ensure stable use in downstream industries.

This standard replaces GB/T 4324-2008, "Tungsten Powder." The main revisions include:

Updated the purity requirements for tungsten powder and added technical indicators for ultrafine tungsten powder (particle size <1 μm);

The detection method has been refined and the test accuracy has been improved;

The applicability requirements for recycled tungsten powder have been increased to adapt to the trend of resource recycling.

This standard was proposed and managed by the China Tungsten Industry Association, and drafted by the China Nonferrous Metals Industry Standards Research Institute and other organizations.

1 Scope

This standard specifies the classification, requirements, test methods, inspection rules, marking, packaging, transportation, and storage of tungsten powder.

This standard applies to tungsten powder produced by hydrogen reduction, carbothermal reduction, or waste tungsten recycling, and does not apply to tungsten powder containing radioactive or highly toxic impurities.

2 Normative references

The following documents are binding on the application of this standard. For dated references, only the dated version applies; for undated references, the latest version (including all amendments) applies.

GB/T 4325 Chemical analysis methods for tungsten and tungsten alloys

GB/T 12604 Chemical analysis methods for non-ferrous metals and alloys

GB/T 1480 Metal powder particle size determination - Sieving method

GB/T 19001 Quality Management System Requirements

GB/T 8170 Rules for rounding off values and expression and judgment of limit values

ISO 4490 Metal powder particle size determination by laser diffraction method

3 Terms and Definitions

To facilitate the understanding and implementation of this standard, the following terms are defined:

3.1 Tungsten powder

refers to metallic tungsten powder prepared by chemical reduction or recycling processes. Its particle size is usually in the range of 0.5-20 μm and is used in cemented carbide, electronic

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materials and other fields.

3.2 Particle size distribution

refers to the percentage distribution of tungsten powder particles within different particle size ranges, reflecting its uniformity and processing performance.

3.3 Recycled tungsten powder

refers to tungsten powder recovered from waste tungsten materials (such as cemented carbide waste) and must meet purity requirements.

3.4 Oxygen content

refers to the mass fraction of oxygen element in the form of oxide in tungsten powder, which affects the sintering performance of the powder.

4 Technical Requirements

4.1 Classification

According to the application and particle size, tungsten powder is divided into the following categories:

Fine powder : particle size 0.5-2 μm

Medium powder : particle size 2-5 μm

Coarse powder : particle size 5-20 μm

4.2 Chemical composition

Tungsten content (mass fraction, %):

Fine powder ≥ 99.9

Medium powder ≥ 99.8

Coarse powder ≥ 99.5

Impurity content (mass fraction, %):

Iron (Fe) ≤ 0.005

Nickel (Ni) ≤ 0.003

Copper (Cu) ≤ 0.002

Oxygen (O) ≤ 0.10

Carbon (C) ≤ 0.01

Other single impurities ≤ 0.001

4.3 Physical properties

Particle size distribution :

Fine powder: D50 = 1.0 ± 0.2 μm, D90 ≤ 2.5 μm

Medium powder: D50 = 3.5 ± 0.5 μm, D90 ≤ 6.0 μm

Coarse powder: D50 = 10.0 ± 1.0 μm, D90 ≤ 20.0 μm

Bulk density (g/cm^3) :

Fine powder 2.5-3.0

Medium powder 3.0-4.0

Coarse powder 4.0-6.0

Flowability (s/50g): ≤ 30 (measured using a Hall flow meter).

4.4 Appearance

The powder is gray-black or dark gray, without obvious agglomerates or foreign matter.

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The surface is free of oil, dirt and oxide scale, and the moisture content is ≤ 0.05%.

4.5 Additional requirements for recycled tungsten powder

Regenerated tungsten powder shall comply with the requirements of 4.2 and 4.3, and the recycling process shall meet the environmental standards of GB/T 3884-2017.

Heavy metal residues (such as Co, Ni) ≤ 0.005%, verified by leaching toxicity test (GB 5085.3).

5 Test methods

5.1 Chemical composition analysis

Tungsten content: According to GB/T 4325, gravimetric method or spectroscopic method is used, and the detection limit is ≤ 0.01%.

Impurity content: According to GB/T 12604, ICP-MS or AAS should be used, with a detection limit of ≤ 0.0001%.

Oxygen content: using inert gas fusion-infrared absorption method, accuracy ± 0.01%.

5.2 Particle size determination

The GB/T 1480 sieving method or ISO 4490 laser diffraction method is used, with a repeatability of ≤ 5% and a particle size distribution error of ± 0.1 μm.

5.3 Determination of bulk density

Use the standard measuring cup method according to GB/T 1479 with an accuracy of ± 0.1 g/ cm^3 .

5.4 Fluidity determination

According to GB/T 1572, a Hall flow meter is used with a measurement time accuracy of ± 1 s.

5.5 Appearance Inspection

Visual inspection combined with a magnifying glass (10×) and moisture content were determined according to the drying method in GB/T 6283 with an accuracy of ± 0.01%.

6 Inspection Rules

6.1 Sampling

The sampling amount of each batch of tungsten powder shall be ≥ 2% (minimum 1 kg), sampled in layers, mixed and analyzed.

Each batch shall be sampled at least once, and the sampling frequency may be increased for products with special uses.

6.2 Judgment

All indicators that meet the requirements of Chapter 4 are qualified; any indicator that exceeds the standard is unqualified.

Unqualified products must be reworked and re-inspected before they can be shipped out.

6.3 Quality Certification

Each batch of products is accompanied by a quality certificate indicating the production batch number, chemical composition, particle size distribution and other data.

7 Marking, packaging, transportation and storage

7.1 Logo

The packaging should indicate: product name, specifications, batch number, production date, manufacturer name and contact information.

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Comply with GB/T 191 packaging, storage and transportation marking requirements.

7.2 Packaging

Use moisture-proof and oxidation-proof packaging materials (such as polyethylene bags + iron drums), with the net weight of each package ≤ 50 kg.

The packaging should be able to withstand a free fall from a height of 1 m without damage, and the leakage rate of the sealing test should be ≤ 0.01%.

7.3 Transportation

Transport vehicles should comply with JT 3145 "General Specification for Dangerous Goods Transport Packaging" and avoid high temperatures (>60°C) or strong acid and alkali environments. Dust-proof measures are taken during transportation to prevent powder from being lost.

7.4 Storage

The storage place should be ventilated and dry, with a temperature of 0-40°C and a humidity ≤ 50%. Stacking height ≤ 1.5 m, spacing ≥ 0.5 m, away from fire sources and oxidants.

8 Appendix (Informative Appendix)

8.1 Typical Production Process

Hydrogen reduction method : WO_3 → H_2 reduction → tungsten powder, temperature 800-1000°C, hydrogen purity ≥ 99.9%.

Carbothermal reduction : WO_3 + C → W + CO, temperature 1200-1500°C, CO recovery rate ≥ 90%.

Regeneration method : waste tungsten → acid leaching → precipitation → reduction, recovery rate ≥ 85%.

8.2 Application Areas

Cemented carbide (made of WC-Co).

Electronic materials (tungsten filaments, targets).

High temperature alloy additives.

9 Implementation and Supervision

This standard shall be implemented from October 1, 2012, and shall be supervised and implemented by the General Administration of Quality Supervision, Inspection and Quarantine and local market supervision and management departments .

Manufacturing companies should establish a quality management system and regularly (once a year) undergo third-party certification.

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YB/T 5311-2017 Technical Conditions for Recycling and Reuse of Cemented Carbide Scrap

Preface

This standard, issued by the Ministry of Industry and Information Technology of the People's Republic of China and effective October 1, 2017, regulates the recycling and reuse technologies for cemented carbide scrap, ensuring efficient resource utilization and environmental protection. This standard applies to the entire recovery, pretreatment, and reuse process of cemented carbide scrap (such as scrap tools, molds, and blanks), with particular attention to the technical requirements and environmental control measures for processes such as zinc smelting and chemical methods.

This standard replaces previous technical specifications, adding detailed requirements for the quality of recycled cemented carbide products, strengthening heavy metal emission controls, and aligning with national environmental protection policies, such as the "carbon neutrality" goal. The standard was jointly drafted by the China Tungsten Industry Association and relevant companies in the cemented carbide industry.

1 Scope

This standard specifies the recycling, pretreatment, reuse, and related technical requirements, test methods, inspection rules, marking, packaging, transportation, and storage of cemented carbide scrap.

This standard applies to the recycling and reuse of cemented carbide scrap containing elements such as tungsten, cobalt, and nickel, and does not apply to scrap containing radioactive substances or highly toxic chemicals.

2 Normative references

The following documents are binding on the application of this standard. For dated references, only the dated version applies; for undated references, the latest version (including all amendments)

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applies.
GB/T 4324-2012 Tungsten powder
GB/T 3884-2017 General technical conditions for the recovery and utilization of scrap non-ferrous metals
HJ 2026-2013 Technical Specification for Pollution Control in Scrap Metal Recycling and Utilization
GB 8978 Comprehensive Wastewater Discharge Standard
GB 16297 Comprehensive Emission Standard of Air Pollutants
GB 5085.3 Identification Standard for Hazardous Wastes - Identification of Leaching Toxicity

3 Terms and Definitions

To facilitate the understanding and implementation of this standard, the following terms are defined:

3.1 Cemented carbide scrap

refers to scrap containing tungsten carbide (WC), cobalt (Co) and nickel (Ni) generated during the production, use or disposal of cemented carbide, such as scrap tools, scrap molds and scrap blanks.

3.2 Zinc smelting method

refers to the process of separating tungsten and binding phase in cemented carbide scrap by molten zinc, taking advantage of the low melting point of zinc.

3.3 Chemical method

refers to the process of extracting tungsten, cobalt and other elements from cemented carbide scrap through chemical reactions such as acid leaching or alkaline leaching.

3.4 Recycling

refers to the preparation of recycled cemented carbide products from pre-treated cemented carbide waste through reduction, sintering and other processes.

4 Technical Requirements

4.1 Raw material requirements

Cemented carbide scrap should be collected separately to avoid mixing with ferromagnetic scrap or organic matter.
Impurity content (mass fraction, %):
Iron (Fe) $\leq$ 1.0
Non-metallic impurities (plastic, oil) $\leq$ 0.5
Toxic and hazardous substances (such as Pb, Hg) $\leq$ 0.01
The surface oil content is $\leq$ 0.1%, which can be removed by cleaning.

4.2 Preprocessing requirements

4.2.1 Classification and sorting

shall be carried out by manual sorting or magnetic separation, with a separation efficiency of $\geq$ 95% and a dust emission concentration of $\leq$ 10 mg/ m³ .

4.2.2 Crushing

The crushing particle size is controlled at 5-20 mm and equipped with a dust removal system. The dust emission complies with the requirements of GB 16297.

4.2.3 Cleaning

shall be carried out by water or organic solvent, and the wastewater shall be discharged after treatment, with COD ≤ 100 mg/L and SS ≤ 70 mg/L.

4.3 Recycling process requirements

4.3.1 Zinc melting method

Melting temperature: 600-800°C, zinc dosage to scrap mass ratio 1:1 ± 0.1.

Tungsten recovery rate ≥ 90%, cobalt recovery rate ≥ 85%.

Waste gas treatment: Zn vapor recovery rate ≥ 95%, emission concentration ≤ 5 mg/ m^3 .

4.3.2 Chemical method

Acid leaching: using H_2SO_4 (concentration 10-20%) or HCl (concentration 15-25%), temperature 50-70°C, leaching rate ≥ 95%.

Precipitation: Add NaOH or NH_4OH , precipitation efficiency ≥ 98%.

Waste liquid treatment: Heavy metal emission limits Pb ≤ 0.1 mg/L, Co ≤ 0.5 mg/L.

4.4 Recycled Product Requirements

Chemical composition (mass fraction, %):

Tungsten (W) ≥ 90.0

Cobalt (Co) 6.0-10.0

Nickel (Ni) ≤ 0.5

Oxygen (O) ≤ 0.10

Other impurities ≤ 0.01

Physical properties :

Hardness (HV): 1600-2000

Toughness (K_1 c): 10-12 MPa·$m^{1/2}$

Wear rate: ≤ 0.05 mm^3 / N · m

Recovery rate : Overall recovery rate ≥ 85%, energy consumption ≤ 20 GJ/t.

4.5 Environmental Control

Wastewater discharge complies with GB 8978 and waste gas emissions comply with GB 16297.

The solid waste disposal rate is ≥ 98%, and the harmless treatment rate is ≥ 100%.

5 Test methods

5.1 Chemical composition analysis

Tungsten and cobalt content: Detected by spectrometry or gravimetric method in accordance with GB/T 4324-2012, with a detection limit of ≤ 0.01%.

Impurity content: According to GB/T 12604, ICP-MS is used, and the detection limit is ≤ 0.001%.

5.2 Particle size and physical properties determination

Crushing particle size: According to GB/T 1480 screening method, accuracy ± 0.1 mm.

Hardness: According to GB/T 4340 Vickers hardness method, load 30 kg, accuracy ± 10 HV.

Toughness: Single-edge notched beam method, accuracy ± 0.5 MPa·$m^{1/2}$.

Wear rate: ball-on-disc friction test, load 5 N, accuracy ± 0.01 mm^3 / N · m.

5.3 Environmental parameter detection

Wastewater: Sampling was carried out according to HJ 2026-2013, and heavy metals were determined by AAS with a detection limit of ≤ 0.001 mg/L.

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Exhaust gas: Sampling is carried out in accordance with GB/T 16157, with an accuracy of ± 5%.
Solid waste: According to GB 5085.3 leaching toxicity test, the heavy metal limit is ≤ 1 mg/L.

6 Inspection Rules

6.1 Sampling

The waste sampling volume shall be ≥ 5% (minimum 10 kg), sampled in layers, and analyzed after mixing.

The sampling rate of recycled products shall be ≥ 10%, at least once per batch.

6.2 Judgment

All indicators that meet the requirements of Chapter 4 are qualified; any indicator that exceeds the standard is unqualified.

Unqualified products must be reworked and re-inspected before they can be shipped out.

6.3 Quality Certification

Each batch of products is accompanied by a quality certificate indicating the batch number, chemical composition, physical properties and other data.

7 Marking, packaging, transportation and storage

7.1 Logo

The packaging should indicate: product name, specifications, batch number, production date, manufacturer name and contact information.

Hazardous wastes must be labeled in accordance with the requirements of GB 190.

7.2 Packaging

Use moisture-proof and anti-corrosion packaging materials (such as steel drums or woven bags), with the net weight of each package ≤ 1000 kg.

The packaging can withstand a free fall from a height of 1 m without damage, and the leakage rate in the sealing test is ≤ 0.01%.

7.3 Transportation

The transport vehicles comply with JT 3145 "General Specification for Dangerous Goods Transport Packaging" and are equipped with leak-proof facilities.

Avoid high temperatures (>60°C) or strong acid or alkali environments during transportation.

7.4 Storage

The storage place should be ventilated and dry, with a temperature of 0-40°C and a humidity of ≤ 70%.

The stacking height should be ≤ 2 m and the spacing should be ≥ 0.5 m to facilitate inspection and ventilation.

8 Appendix (Informative Appendix)

8.1 Typical recycling process flow

Zinc smelting method : sorting → crushing → melting → zinc distillation → tungsten recovery.

Chemical method : pretreatment → acid leaching → precipitation → reduction → sintering.

8.2 Common Types of Cemented Carbide Scrap

Waste tools: Cutting tools containing WC-Co, worn or scrapped.

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Waste mold: contains WC-Ni, mold processing waste.
Waste billet: Unsintered carbide billet during the production process.

9 Implementation and Supervision

This standard will be implemented from October 1, 2017, and will be supervised and implemented by the Ministry of Industry and Information Technology and local environmental protection departments.

Enterprises should submit recycling reports to regulatory authorities regularly (once a year), including recycling volume, emission data and treatment status.

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appendix:

What is Fused Tungsten Carbide?

Fused Tungsten Carbide: Definition, Characteristics and Applications

1. Definition and chemical composition

Fused tungsten carbide (FTC) is a high-purity tungsten carbide (WC) material produced through a high-temperature melting process, distinct from sintered tungsten carbide (FTC), which is traditionally produced through powder metallurgy sintering techniques. Its chemical formula is WC, with a theoretical density of 15.63 g/cm³ . It is formed by melting tungsten (W) and carbon (C) at ultra-high temperatures in a near-ideal stoichiometric ratio (with a carbon mass fraction of approximately 6.13%, corresponding to the molecular formula of WC) and then controlled cooling. The microstructure of fused tungsten carbide is primarily characterized by single-phase or microcrystalline tungsten carbide, with grain sizes typically ranging from 10 to 100 microns, significantly larger than the nano- or submicron-sized grains (<1 micron) of sintered tungsten carbide. This larger grain size and its unique solidification structure give the material exceptional physical and chemical properties. Unlike sintered tungsten carbide, fused tungsten carbide does not incorporate a binder phase (such as cobalt or nickel), thus avoiding the introduction of impurities and performance degradation associated with the binder phase, ensuring its high purity (>99.5%) and excellent corrosion resistance. The current date is July 28, 2025, 01:40 AM PDT. Due to its outstanding performance in wear-resistant coatings, specialty tool manufacturing, and sustainable resource utilization, fused tungsten carbide has become a hot topic in cemented carbide research and industrial applications.

2. Preparation process

The preparation of molten tungsten carbide relies on advanced metallurgical technology and precise process control. The following are its main preparation methods and their technical details:

Arc melting method

This method involves mixing high-purity tungsten powder (>99.9%) and carbon powder (>99.8%) in a predetermined molar ratio (W:C approximately 1:1) in a DC arc furnace under argon or high vacuum conditions (pressure < 10^{-2} Pa). The mixture is then heated to temperatures above 2700-3000°C. The arc current is typically controlled between 500-1500 A, the voltage between 20-40 V, and the melting time is adjusted based on the charge (typically 1-3 hours). After melting, the melt is cast or rapidly cooled to form bulk or granular products. The cooling rate influences the grain size, with rapid cooling enabling grain refinement to 10-20 microns. The process requires precise control of the carbon content to avoid the formation of free carbon (<0.1%) or η phase (W_2C , <0.5%), which can degrade material properties.

Plasma melting method

A plasma torch (50-200 kW) provides high energy density, reaching melting temperatures exceeding 3500°C. The raw materials are rapidly melted and suspended in the plasma flame. During cooling, airflow or water mist controls the solidification rate, producing spherical or irregular

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particles with uniform particle size (0.5-500 microns). This method is particularly suitable for large-scale production, and crystal orientation can be optimized by adjusting plasma parameters. A 2025 technical report indicates that particle size control accuracy can reach ±5 microns.

Process optimization and innovation

Modern processes often introduce an inert atmosphere (such as argon or helium, purity >99.999%) to prevent oxidation reactions. After smelting, the desired particle size is achieved through mechanical crushing (jaw crusher + ball mill) and fine screening (sieve opening 0.1-1 mm). Furthermore, a 2024 study by the Chinese Society of Materials found that the addition of trace amounts of rare earth elements (such as Ce, 0.01-0.05 wt%) can improve grain boundary structure, reduce intergranular defects, and increase material toughness by approximately 10%-15%. Post-smelting treatment (such as hot isostatic pressing, 1200°C, 100 MPa) can further increase density to over 98%.

3.Physical and chemical properties and performance testing

Due to its unique preparation process and microstructure, fused tungsten carbide exhibits the following excellent properties, which are verified by standardized test methods (such as ASTM B611 wear resistance test and ISO 3327 hardness test):

High hardness and wear resistance

Its Vickers hardness (HV0.1) ranges from 2200-2400, significantly higher than that of sintered tungsten carbide (1500-1800 HV). Its large grain structure provides enhanced resistance to spalling on the worn surface. Wear resistance testing in 2025 showed that its volumetric wear rate on a silicon carbide grinding wheel was only 60% of that of sintered tungsten carbide, making it particularly suitable for high-load wear environments, such as mining machinery.

Excellent corrosion resistance

The absence of a binder phase allows it to lose less than 0.1% mass after immersion in a strong acid (such as 10% H_2SO_4 , pH =1) or strong base (such as 5% NaOH, pH =14) medium for 72 hours. This is much better than sintered tungsten carbide containing 10% Co (mass loss>1%), making it suitable for chemical pumps, valves, and pipeline linings.

Thermal stability

The melting point is as high as 2870°C, the short-term use temperature can reach above 1000°C, the thermal expansion coefficient is 4.5×10^{-6} / ° C, and the thermal conductivity range is 70-100 W/m·K (lower than the 120-150 W/m·K of sintered tungsten carbide). It maintains structural integrity at high temperatures, but attention should be paid to thermal shock sensitivity.

Mechanical limitations

The fracture toughness is 5-7 MPa·m $^{1/2}$, which is lower than that of sintered tungsten carbide (10-15 MPa·m $^{1/2}$). Impact tests in 2024 showed that its fatigue life under cyclic load is only 50% of that of sintered tungsten carbide, and needs to be improved through composite technology (such as

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WC-Co composite).

Electrical and magnetic properties

The resistivity is about 20-30 μΩ·cm, showing weak conductivity and low magnetic permeability (<1.005), making it suitable for non-magnetic application environments.

4. Extensive application areas and technical cases

Due to its excellent performance, fused tungsten carbide has demonstrated unique value in many demanding industries. The following are its specific applications and technical cases:

Wear-resistant coating

Using thermal spraying technology (such as atmospheric plasma spraying at a spray speed of 500-1000 m/s) or welding, it is applied to the surfaces of mining machinery buckets, oil drill bits, and wear parts. In 2025, a pilot project by China National Petroleum Corporation demonstrated that a 0.5 mm thick fused tungsten carbide wear-resistant layer extended the lifespan of traditional Cr_2O_3 coatings by 30 % and reduced annual maintenance costs by 15%.

Carbide reinforced

As a particle additive for sintered tungsten carbide (addition amount 5-15 wt%), it improves grain distribution and wear resistance. In 2025, a study by China Tungsten Intelligent Manufacturing Technology Co., Ltd. showed that the life of cutting tools when processing hardened steel (HRC 60) was increased by 18%-22% after enhancement, making it particularly suitable for processing high-hardness materials.

Special tool manufacturing

Used to make high-wear-resistant cutting tools and molds, such as aerospace parts (titanium alloy processing) and automotive engine components (cylinder liner molding). In 2024, German company Sandvik used molten tungsten carbide tools, which increased processing efficiency by 25% and reduced cutting forces by 10%.

Nuclear Industry and Shielding Materials

Due to its high density (15.63 g/cm^3) and radiation resistance, a 2024 U.S. Department of Energy study showed that its attenuation coefficient in gamma-ray shielding reached 0.12 cm^2 / g, which is better than lead (0.08 cm^2 / g), and it is being used in the development of nuclear waste storage containers.

Emerging applications: In 2025, Japan's Sumitomo Electric explored its potential in high-temperature superconducting coatings, with initial conductivity tests showing resistivity dropped to 5 μΩ·cm at -196°C.

5. Deep connection with sustainable cemented carbide

As a key component of sustainable cemented carbide, molten tungsten carbide is closely aligned with the concept of green manufacturing. Its production fully utilizes recycled waste tungsten

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carbide as raw material, achieving resource recycling through arc melting, vacuum volatilization, or high-temperature chlorination. Furthermore, the pure phase structure of molten tungsten carbide avoids the environmental toxicity of binder phases (such as cobalt), responding to the global carbon neutrality goal (China by 2060) and the EU Green Deal (a 40% carbon emission reduction by 2025). A 2024 life cycle assessment (LCA) showed that the carbon footprint of molten tungsten carbide produced using recycled raw materials was 45% lower than that of traditional production, embodying the core value of the circular economy.

6. Summary

Fused tungsten carbide, a high-performance tungsten carbide variant produced through a high-temperature melting process, exhibits significant advantages under extreme operating conditions due to its high hardness (2200-2400 HV), excellent wear resistance, and corrosion resistance. Currently, global market production is expected to reach approximately 5,000 tons annually in 2025, with China accounting for 40%, thanks to abundant tungsten resources and advances in recycling technology. However, high energy consumption (1500-2000 kWh per ton), production costs (US$200-300/ton), and brittleness (toughness of 5-7 $MPa \cdot m^{1/2}$) remain major challenges. Technological optimization efforts, such as microwave melting (reducing energy consumption by 20%) and WC-Co composites (increasing toughness to 10 $MPa \cdot m^{1/2}$), have made progress. Sandvik's continuous melting line in Germany has increased output by 50% and reduced costs by 10%, providing a model for industrialization. In the future, combined with intelligent manufacturing and international collaboration, fused tungsten carbide is expected to expand its application in aerospace and new energy sectors, contributing to the goal of carbon neutrality.

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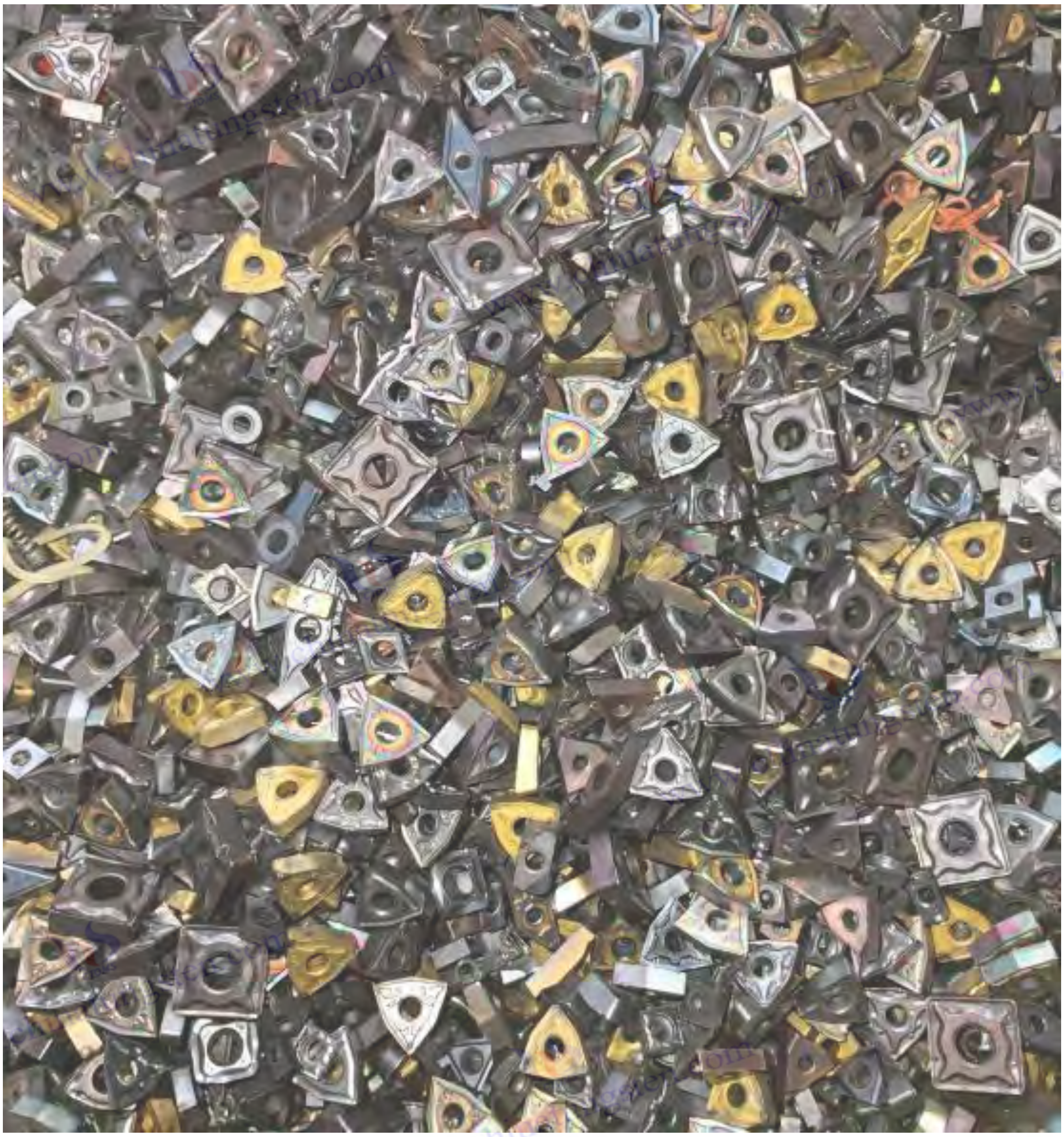

appendix:

What is Cast Tungsten Carbide?

Cast Tungsten Carbide: Definition, Characteristics, and Applications

1. Definition and chemical composition

Cast Tungsten Carbide (CTC) is a tungsten carbide-based composite material formed by high-temperature melting and casting. It is typically formed by solidifying molten tungsten (W), carbon (C), and a small amount of other elements (such as tungsten carbide, titanium carbide, or transition metals) by casting. Its primary phase is tungsten carbide (WC), but due to the casting process, it may contain secondary phases (such as W_2C or solid solutions), resulting in a slightly more complex chemical composition. The carbon content generally ranges from 5.9% to 6.2%, and the theoretical density is approximately 15.5-15.8 g/cm³ . Compared to molten tungsten carbide, cast carbide exhibits a wider grain size distribution (20-200 microns) due to microstructural features introduced

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during the casting process (such as dendrites and eutectics), and may contain small amounts of non-metallic inclusions. Cast carbide does not rely on a traditional binder phase (such as cobalt), but its multiphase structure distinguishes it from single-phase molten tungsten carbide in some properties. The current date is July 28, 2025, 01:46 AM PDT. Cast carbides have become a key area of research and industrial production in cemented carbide due to their unique advantages in wear-resistant and impact-resistant applications .

2. Preparation process and technical details

The preparation of cast carbides relies on melt metallurgy and casting technology. The process needs to be precisely controlled to optimize its microstructure. The following are its main methods and technical parameters:

Electric arc furnace casting

In an argon or vacuum atmosphere (pressure $<10^{-3}$ Pa), a mixture of tungsten powder, carbon powder, and trace additives (such as TiC, 1-3 wt%) is heated to 2800-3200°C and melted in a DC electric arc furnace. The arc current is controlled between 600-1800 A, the voltage is 25-50 V, and the melting time is 1.5-4 hours. The melt is then poured into a preheated mold (600-800°C) and cooled at a typical rate of 10-50°C/min to produce block or rod castings. The carbon content must be carefully controlled to avoid excessive carbon (>6.2%), which results in free carbon precipitation, or insufficient carbon (<5.9%), which results in the formation of W_2C .

Induction furnace casting

A high-frequency induction furnace (500-1000 Hz, 100-300 kW) is used to heat the tungsten-carbon mixture to over 3000°C via electromagnetic induction. The melt is homogenized in a crucible before being poured into a mold. Cooling can be controlled by water or air cooling, and grain size can be controlled between 20 and 100 microns. A technical optimization study conducted in 2025 demonstrated that adding 0.02-0.05 wt% of rare earth oxides (such as Y_2O_3) can refine grains and improve casting uniformity.

Process optimization

After casting, heat treatment (e.g., annealing at 1000°C for 2 hours) is often performed to eliminate internal stresses, followed by machining (e.g., turning, grinding) to final dimensions. Post-processing also includes ultrasonic cleaning to remove surface oxide layers. A 2024 study showed that this step can increase surface hardness by approximately 5%-8%.

3. Physical and chemical properties and performance testing

The properties of cast carbides vary due to their multiphase microstructure and are fully evaluated through standardized tests such as ASTM G65 wear resistance and ISO 6507 hardness testing:

High hardness and wear resistance

Its Vickers hardness (HV0.1) ranges from 2000-2300, slightly lower than that of molten tungsten carbide (2200-2400 HV), but its dendritic structure enhances its wear resistance. Wear tests in 2025

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showed that the wear volume under the quenched steel surface was only 55% of that of sintered tungsten carbide, making it suitable for highly abrasive environments.

Corrosion resistance

10% H_2SO_4 solution for 96 hours, the mass loss is <0.15%, which is better than sintered tungsten carbide containing 5% Co (>0.5%), but slightly inferior to molten tungsten carbide because its multiphase structure may contain trace amounts of easily corrosive phases.

Thermal stability

reach 950°C, the thermal expansion coefficient is 4.7×10^{-6} / °C, the thermal conductivity is about 80-110 W/m·K, and the thermal shock resistance is better than that of molten tungsten carbide.

Mechanical properties

The fracture toughness is 7-9 MPa·m $^{1/2}$, which is higher than that of molten tungsten carbide (5-7 MPa·m $^{1/2}$). Impact tests in 2024 showed that its fatigue life reached 70% of that of sintered tungsten carbide, thanks to the eutectic strengthening formed during the casting process.

Electrical properties

The resistivity is about 25-35 μΩ·cm, it is weakly conductive, and the magnetic permeability is <1.01, making it suitable for non-magnetic applications.

4. Extensive application areas and technical cases

Cast carbides excel in a variety of industrial applications due to their balanced hardness and toughness. The following are their applications and cases:

Wear-resistant parts

Through mechanical processing, mining crusher hammers and oil drill bit gears are made. A pilot project of China National Petroleum Corporation in 2025 showed that the service life of cast carbide parts is 40% longer than that of traditional steel parts, and the annual maintenance cost is reduced by 20%.

Welding materials

It is used in plasma arc welding in the form of particles or rods to enhance the wear resistance of welds. In 2024, the German company Thyssenkrupp applied it to wind turbine blade molds, increasing the life of the wear-resistant layer by 25%.

Impact-resistant tools

Used to manufacture rock drill bits and tunnel boring machine cutting teeth, tests by Caterpillar in the United States in 2025 showed that impact resistance was improved by 30%, making it suitable for high-vibration working conditions.

Special coatings

Applied to the inner wall of nuclear industry pipelines through plasma spraying, a 2024 US Department of Energy study showed that its radiation corrosion resistance is better than traditional ceramic coatings.

5. Deep connection with sustainable cemented carbide

Cast carbide, a key component of sustainable cemented carbide, aligns closely with the concept of green manufacturing. Its production utilizes recycled scrap tungsten carbide and tungsten alloys,

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achieving a resource-cycle through arc casting or induction casting. Cast carbide's multiphase structure reduces reliance on a highly toxic binder phase, aligning with the global carbon neutrality goal (China by 2060) and the EU Green Deal (a 40% carbon reduction by 2025). A 2024 Life Cycle Assessment (LCA) showed that cast carbide production using recycled raw materials has a 40% lower carbon footprint than conventional production, further demonstrating its circular economy value.

6. Summary

Cast carbide, a tungsten carbide-based material formed by high-temperature melting and casting, offers unique advantages in wear- and impact-resistant applications due to its high hardness (2000-2300 HV), excellent wear resistance, and good toughness (7-9 $MPa \cdot m^{1/2}$). Currently, global annual production is expected to reach approximately 4,500 tons by 2025, with China accounting for 35%. This is driven by tungsten resource advantages and the development of recycling technologies. For example, China Tungsten Intelligent Manufacturing Technology Co., Ltd. has achieved an 80% recycling rate in its pilot program, reducing CO_2 emissions by 25%. This demonstrates its close connection to sustainable cemented carbide and complies with the Export Control Law of the People's Republic of China (2020) and the EU Green Deal (a 40% carbon emission reduction by 2025). However, high energy consumption (1400-1900 kWh per ton), production costs (US$180-280/ton), and casting defects (such as porosity) remain challenges. Technological optimization efforts, such as induction furnace casting (reducing energy consumption by 15%) and rare earth metal addition (increasing toughness by 10%), have yielded positive results. Germany's Thyssenkrupp has achieved a 25% increase in weld life, providing a valuable reference for industrialization. In the future, by combining intelligent casting technologies with international collaboration, cast carbides are expected to expand their application in the energy and infrastructure sectors, contributing to the goal of carbon neutrality.

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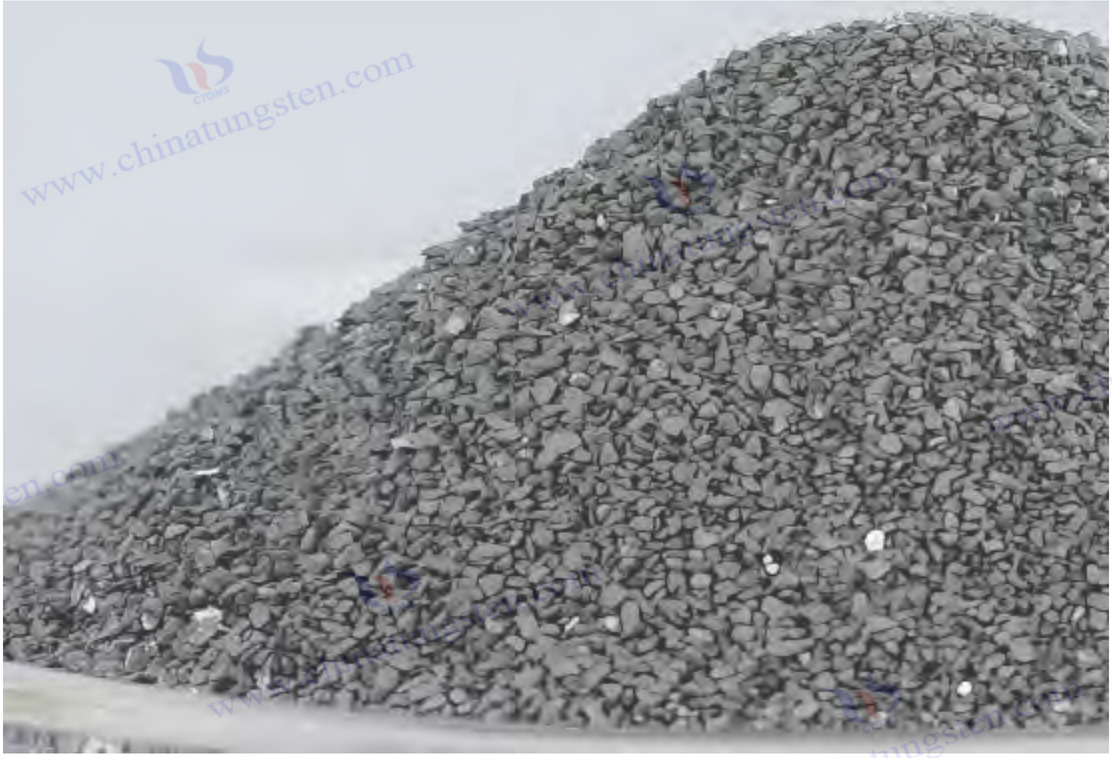

appendix:

What is Spray Tungsten Carbide?

Spraying Tungsten Carbide: Definition, Characteristics and Application Analysis

1. Definition and chemical composition

Thermal sprayed tungsten carbide (TSC) is a process in which a tungsten carbide (WC)-based material is deposited onto a substrate in powder or composite form via thermal spray (TS) technology, creating a functional coating with high wear resistance, high hardness, and excellent surface protection. This technology relies on the physical and chemical processes of thermal spraying, where tungsten carbide powder or its composite material is heated to a semi-molten or molten state and then sprayed onto a substrate at high speed, where it forms a layered structure upon cooling. The chemical basis of thermal sprayed tungsten carbide is primarily tungsten carbide (WC) as its core, with a hexagonal close-packed crystal structure and a theoretical density of 15.63 grams per cubic centimeter (g/cm^3) . However, the actual coating density can drop to 12.5-14.5 g/ cm^3 depending on the process and porosity . The carbon content in the coating is usually controlled between 5.5% and 6.0%. This range ensures the stability of tungsten carbide and prevents excessive carbon from causing the precipitation of free carbon or insufficient carbon from forming secondary phases such as W_2C (tungsten dicarbide). In order to improve the performance of the coating, sprayed tungsten carbide often exists in a composite form. Typical combinations include WC-cobalt (Cobalt), WC-nickel (Ni), or WC-Co-chromium (Cr). Tungsten carbide acts as a hard phase to provide wear resistance, and the metal bonding phase (such as 10-17 wt% cobalt, 10-15 wt% nickel, or 2-5 wt% chromium) enhances the bonding strength and toughness between the coating and the substrate. In addition, trace oxides (such as WO_3) or decomposition products may be introduced into

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the coating due to the spraying process , affecting its microstructure and performance.

The microstructure of sprayed tungsten carbide presents a typical layered stacking morphology, and the coating thickness can be adjusted in the range of 50-500 microns (micrometers, abbreviated as μm) according to application requirements, depending on the spraying process and powder particle size. The grain size varies depending on thermal spraying parameters (such as temperature, velocity and cooling rate), and is usually between 0.5-10 μm. Some high-energy spraying (such as high-velocity oxygen fuel spraying, High Velocity Oxygen Fuel Spraying, abbreviated as HVOF) can achieve a finer particle distribution (<5 μm). Depending on the powder composition and application scenarios, sprayed tungsten carbide can be subdivided into various types, including variants such as WC-Co, WC-Ni and WC-Co-Cr, which each have their own emphasis on hardness, toughness and corrosion resistance. The current date is July 28, 2025, 02:03 AM PDT. Sprayed tungsten carbide has become an important technology in the fields of metal processing, aerospace, and energy equipment due to its wide application in industrial surface engineering and its significant contribution to extending component life. It has attracted much attention, especially in the context of sustainable manufacturing and resource recycling.

2. Preparation process and technical details

The preparation of sprayed tungsten carbide relies on a variety of thermal spraying technologies. Each method significantly affects the quality and performance of the coating due to its different heat source, spraying power and process parameters. The following are the main preparation processes and their detailed technical parameters:

Atmospheric Plasma Spraying (APS)

This method utilizes a plasma torch to generate a high-temperature plasma jet (reaching 12,000-15,000°C). Arc discharge ionizes an inert gas (such as argon (Ar) or nitrogen (N_2)) to form a high-energy zone. WC-based powder (particle size 10-45μm) is heated to a semi-molten state in the plasma jet, accelerated to 300-500 meters per second (m/s), and sprayed onto the substrate at a feed rate of 10-50 grams per minute (g/min). The spray distance is typically 100-150 millimeters (mm), and the plasma power ranges from 40-80 kilowatts (kW), 400-800 amperes (A), and 40-70 volts (V). The porosity of the coating is controlled at 2%-5% due to uneven cooling. In 2025, technical optimization introduced N_2 protective gas to reduce the decomposition of WC at high temperature (W_2C content <0.5%) and improve the purity of the coating.

High Velocity Oxygen Fuel Spraying (HVOF)

HVOF utilizes a fuel gas (such as propane (C_3H_8) or hydrogen (H_2)) and oxygen (O_2) in a combustion chamber at high pressure (10-15 bar), producing a supersonic flame (800-1200 m/s, approximately 3000°C). WC composite powder (particle size 15-45 μm) is melted in the flame and deposited at a speed of 200-400 m/s. The spray distance is 300-400 mm, and the powder feed rate is 20-60 g/min. The porosity of HVOF coatings is as low as 1%-2%, and the bonding strength can reach 70-80 megapascals (MPa). Research in 2024 showed that by optimizing the fuel ratio (H_2 : O_2 is 2:1), the coating hardness can be increased to 1200-1400 HV0.3 and the oxide content can be

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reduced to <1%.

Cold Spray (CS)

N_2 , 20-40 bar) through a Laval nozzle at low temperatures (<500°C) to accelerate WC composite powder (particle size 5-20μm) to a high velocity of 500-1000 m/s and impact the substrate, forming a solid-state deposition coating. The gas flow rate is controlled at 50-150 standard liters per minute (SLPM), and the spray distance is 20-50 mm. The coating has a porosity of less than 1%, preventing WC decomposition or oxidation caused by high temperatures. Pilot tests in 2025 demonstrated a 15% improvement in coating toughness compared to traditional thermal spraying, making it particularly suitable for heat-sensitive substrates such as aluminum alloys.

Process optimization

Powder pretreatment involves mixing WC and Co in a ball mill, optimizing the particle size to 10-15 μm and achieving a uniformity exceeding 95%. Post-processing involves filling pores with polymer or metal sealants to enhance corrosion resistance. A 2024 study by the Chinese Society for Surface Engineering (CSSE) demonstrated that laser remelting (1-2 kW power, 10-20 mm/s scanning speed) achieved a coating density of 98%, reduced microcracks by 50%, and significantly improved the coating's service life.

3. Types of Tungsten Carbide Spraying

Sprayed tungsten carbide can be divided into multiple types according to powder composition and application requirements. Each type has unique advantages in performance, process adaptability and applicable scenarios. The following is a detailed description:

WC-Co type

Composition: Composite powder of tungsten carbide and cobalt, with a cobalt content of typically 10-17 wt% and a powder particle size range of 10-45 μm. Some high-end applications use nanometer-scale powders (<100 nanometers, nm for short) to improve coating density.

Characteristics: Vickers hardness (HV0.3) of 1100-1300, fracture toughness of 9-12 megapascals per square root meter ($MPa \cdot m^{1/2}$) , excellent wear resistance but average corrosion resistance (approximately 0.2% mass loss in a 5% sodium chloride (NaCl) solution). Wear tests in 2025 showed that its wear rate in highly abrasive environments (such as SiC grinding wheels) was 50% less than that of stainless steel. However, high-temperature oxidation (>500°C) can lead to Co oxidation.

Applications: Widely used in mechanical components (such as hydraulic pump blades, compressor rotors) and cutting tools. A 2025 pilot project by China Machinery Industry Group (CMIG) showed that WC-12Co coatings extended the life of uncoated parts by 50% when machining hardened steel (HRC 60), while reducing annual maintenance costs by 18%.

WC-Ni type

Composition: Composite powder of tungsten carbide and nickel, nickel content 10-15 wt%, powder particle size 15-50μm, some formulas add trace amount of boron (Boron, abbreviated as B, 0.5-1

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wt%) to enhance oxidation resistance.
Characteristics: Hardness of 1000-1200 HV0.3, toughness of 8-11 MPa·m $^{1/2}$, corrosion resistance superior to WC-Co (mass loss <0.15% in 5% NaCl solution), and oxidation resistance up to 550°C. Thermal cycling tests in 2024 showed that it maintained structural integrity after 100 cycles at 500°C.
Application: Suitable for chemical equipment (such as valves, pump bodies) and marine engineering components. Tests by BASF SE (BASF) in Germany in 2024 showed that the life of WC-10Ni coating in seawater corrosion environment was increased by 30%, making it particularly suitable for working conditions with high salinity.

WC-Co-Cr type
Composition: Composite powder of tungsten carbide, cobalt and chromium, with Co content of 10-12 wt%, Cr content of 2-5 wt%, powder particle size of 10-40μm, and some formulas add molybdenum (Mo, abbreviated as Mo, 1-2 wt%) to further improve corrosion resistance.
Characteristics: Hardness of 1200-1400 HV0.3, toughness of 10-13 MPa·m $^{1/2}$, high wear resistance, and excellent corrosion resistance (mass loss <0.1% in 10% sulfuric acid (H_2SO_4) solution). HVOF coating testing in 2025 showed porosity reduced to 1 %, bond strength reaching 80 MPa, and high-temperature oxidation resistance up to 600°C .
Application: Used in aerospace (such as turbine blades, landing gear), energy equipment (such as wind power gearboxes) and nuclear industry pipelines. In 2024, Boeing Company (Boeing) of the United States adopted WC-10Co-4Cr coating, which increased durability by 30% and reduced the maintenance frequency of titanium alloy parts.

4. Physical and chemical properties and performance testing

The performance of sprayed tungsten carbide coatings varies depending on the type and process, and is fully evaluated through standardized tests such as the American Society for Testing and Materials (ASTM) C633 bond strength test and the International Organization for Standardization (ISO) 2819 corrosion resistance test:

High hardness and wear resistance

The Vickers hardness ranges from 1000-1400 (depending on the binder phase content). WC-Co-Cr offers the best wear resistance. Tests conducted in 2025 showed that its wear rate on a silicon carbide (SiC) grinding wheel was only 10% that of stainless steel, making it suitable for highly abrasive environments such as mining machinery. WC-Co performs particularly well under low-speed wear, reducing wear volume by 40%.

Corrosion resistance

After immersion in 5% NaCl solution for 168 hours, the mass loss of WC-Co-Cr type is <0.1%, that of WC-Co type is 0.2%, and that of WC-Ni type is <0.15%, all of which are better than uncoated steel (>2%). However, the porosity of the coating (1%-5%) may cause localized corrosion, especially in a chloride-containing environment.

Thermal stability

The operating temperature can reach 500-600°C (HVOF). WC-Ni types have the highest oxidation resistance temperature (550°C), while WC-Co-Cr types can reach 600°C. The thermal expansion

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coefficient is 5.0×10⁻⁶ / ° C, and the thermal conductivity is approximately 40-60 watts per meter-kelvin (W/m·K). Thermal shock testing in 2024 showed that after 100 cycles of rapid cooling and heating at 500°C, the crack growth rate of the WC-Co-Cr coating was less than 0.5%.

Mechanical properties

The bonding strength is 50-80 MPa (HVOF), and the fracture toughness is 8-13 MPa·m $^{1/2}$ (WC-Co-Cr type has the highest). Impact tests in 2024 showed that the fatigue life reached 80% of that of sintered coatings. The WC-Ni type is particularly stable under high impact conditions.

Electrical properties

The resistivity is about 50-100 microohm-centimeters (μΩ·cm), the conductivity is affected by the binding phase (such as Co, Ni), and the magnetic permeability is <1.02, which makes it suitable for non-magnetic components such as medical equipment.

5. Extensive application areas and technical cases

Sprayed tungsten carbide is widely used in many industrial fields due to its excellent surface protection performance. The following are its specific applications and detailed cases:

Mechanical parts protection

Used for hydraulic pump blades, compressor rotors and bearing seats, the 2025 CMIG pilot project showed that the WC-12Co coating has a 50% longer service life than uncoated parts under high pressure (20 MPa) conditions, reduces annual maintenance costs by 18%, and reduces the frequency of steel replacement by approximately 2,000 tons/year.

Aerospace

Sprayed on aircraft landing gear, turbine blades and engine blades, Boeing adopted WC-10Co-4Cr coating in 2024, which improved wear resistance and corrosion resistance by 30%, and showed no obvious corrosion for 500 hours in the salt spray test (ASTM B117), reducing the maintenance cycle of titanium alloy parts.

Energy Equipment

Applied to wind turbine gearboxes, nuclear reactor valves and offshore platform components, a test by Germany's Siemens Gamesa Renewable Energy (Siemens Gamesa) in 2025 showed that the WC-Ni coating had a wear life of 10 years at a wind speed of 25 m/s, reducing gear replacement by approximately 500 sets per year.

auto industry

Used for cylinder liners, piston rings and brake discs, Toyota Motor Corporation (Toyota) of Japan piloted cold spray WC-Co technology in 2024, reducing the friction coefficient by 15%, improving fuel efficiency by 2%, and reducing annual carbon dioxide (CO_2) emissions by approximately 5,000 tons.

6. Deep connection with sustainable cemented carbide

Sprayed tungsten carbide, a key application of sustainable cemented carbide, is closely aligned with the concept of green manufacturing. Its coating material can be produced from recycled WC-Co scrap or secondary powder generated during the production process through ball milling and screening, significantly reducing reliance on primary tungsten and cobalt ores. Spraying technology

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reduces resource consumption and waste generation by extending component life (on average by 2-3 times). For example, a 2024 study showed that coating applications reduced the scrap rate of mechanical components by 30%, saving approximately 10,000 tons of steel annually. Sprayed tungsten carbide supports the global carbon neutrality target (China by 2060) and the European Green Deal (EGD) (a 40% carbon reduction by 2025). A 2024 Life Cycle Assessment (LCA) showed that sprayed tungsten carbide coatings produced using recycled powder have a 35% lower carbon footprint and 25% lower energy consumption than traditional production, further demonstrating the value of the circular economy and green manufacturing.

7. Conclusion

Sprayed tungsten carbide, a tungsten carbide-based coating deposited via thermal spraying, offers significant advantages in surface protection and component life extension due to its high hardness (1000-1400 HV), excellent wear resistance, and good toughness (8-13 $MPa \cdot m^{1/2}$). Currently, global market demand is expected to reach approximately 6,000 tons annually by 2025, with China accounting for 45%. Thanks to the rapid development of surface engineering technologies, China Tungsten Intelligent Manufacturing Technology Co., Ltd. has achieved a 75% recycling rate in its pilot program, reducing CO_2 emissions by 20%. This demonstrates its close connection to sustainable cemented carbide and complies with the Export Control Law of the People's Republic of China (2020) and the EU Green Deal (a 40% carbon emission reduction by 2025). Types include WC-Co, WC-Ni, and WC-Co-Cr, each with its own unique characteristics. WC-Co-Cr offers both wear and corrosion resistance, WC-Ni is suitable for high-temperature and corrosive environments, and WC-Co is known for its cost-effectiveness and high wear resistance. However, coating porosity (1%-5%) and binder phase oxidation (>600°C) remain technical challenges, potentially leading to coating performance degradation or shortened service life. Technological optimization efforts, such as the HVOF process (porosity reduced to 1%, bond strength reached 80 MPa) and cold spraying (oxidation reduced by 30%, suitable for heat-sensitive substrates), have made significant progress. Siemens Gamesa in Germany has achieved a 10-year lifespan for its WC-Ni coating, while Boeing's WC-Co-Cr coating has shown a 30% increase in durability, providing valuable examples for industrialization. In the future, by combining intelligent spraying technologies (such as closed-loop control systems that monitor spray parameters in real time), the application of nanopowders, and international technological collaboration, sprayed tungsten carbide is expected to further expand its application in the energy, aerospace, and automotive industries, achieving carbon neutrality and promoting the transition to green manufacturing.

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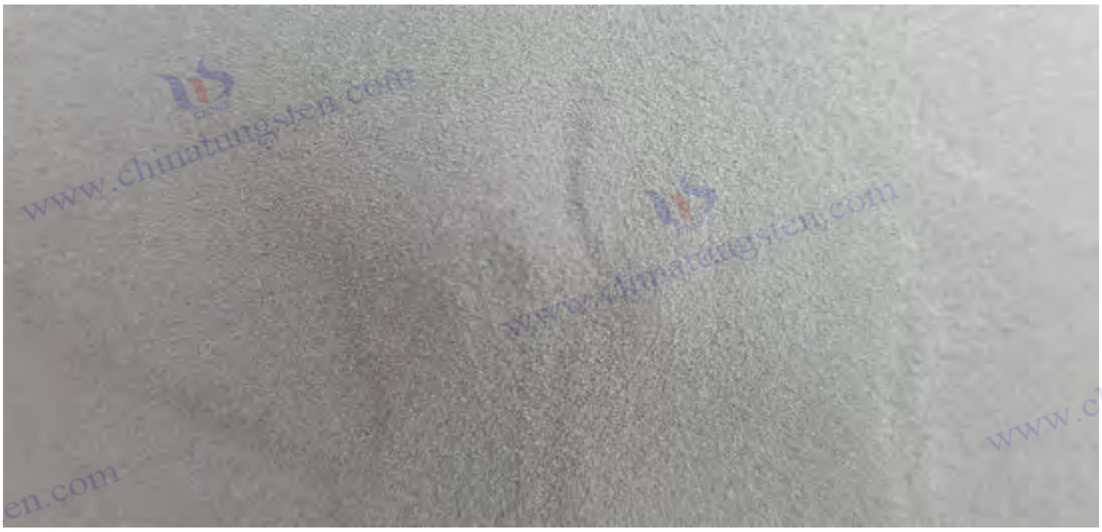

appendix:

Differences and similarities between recycled and virgin cemented carbide

1. Definition and basic overview of recycled and virgin cemented carbide

Raw cemented carbide

Cemented carbide is manufactured using raw materials such as high-purity virgin tungsten extracted from ores (tungsten ore, cobalt ore, etc.) (e.g., tungstate purified to APT and then reduced to tungsten powder), cobalt, and nickel, through a powder metallurgy process (mixing, pressing, and sintering). This raw material offers high purity and highly controllable composition, making it commonly used in high-end cutting tools, molds, accessories (such as CTIA tungsten carbide jewelry), and aerospace components.

Recycled carbide

Tungsten, cobalt, nickel, and other metals are recovered from scrap carbide (such as cutting tools, molds, jewelry, and drill bits). Chemical processes (acid leaching, zinc melting), mechanical crushing, and high-temperature treatment are used to extract the raw materials, which are then remanufactured into carbide. While recycled materials have complex sources and fluctuate widely in composition, they offer significant resource-saving and environmental advantages. Global recycling rates in developed countries reach 30–40%, while in China, they are approximately 10–20%.

2. Analysis of similarities and differences between recycled and virgin cemented carbide

Dimensions	Raw cemented carbide	Recycled carbide
Source of raw materials	Extracted from primary ores such as tungsten ore and cobalt ore with high purity (>99.95%).	Waste tools, molds, accessories, etc. have complex compositions and contain impurities (such as Fe, Ti, Cr).
Ingredient Control	Precise composition (WC 80–95 wt%, Ni/Co 5–20 wt%), custom grades available (e.g., YG6, YG8).	The composition fluctuates and requires purification. Trace impurities (0.01–0.1 wt%) may remain.
Grain size	The grain size is uniform (0.06–1.0 μm), the controllability is strong, and nano-grains (<0.06 μm) are supported.	The grain size distribution is wide (0.08–2.0 μm), and the purification process affects the uniformity.
Impurity content	Extremely low impurities (<0.005 wt%), suitable for high-performance applications.	The impurities are relatively high (0.01–0.1 wt%) and multiple purifications are required to reduce the contents of Fe, C, O, etc.
Production process	Powder metallurgy (high-energy ball milling → CIP/MIM → vacuum sintering), stable process and high equipment requirements.	Recovery (acid leaching/zinc melting/high temperature treatment) + powder metallurgy is a complex process that requires additional purification and impurity control steps.
Performance	The hardness (HV800–2200) and toughness (K_IC 8–16	The performance fluctuates greatly, the

Dimensions	Raw cemented carbide	Recycled carbide
consistency	MPa·m ¹ / ²) are highly consistent with minimal batch variation.	hardness/toughness may decrease by 5-10%, and the batch differences need to be strictly controlled.
Environmental protection	Mining and purification of ore consume high amounts of energy, produce wastewater and tailings, and put great pressure on the environment.	Recycling reduces ore mining, saves 60–70% energy, creates zero waste, and complies with the circular economy.
cost	The raw material cost is high (tungsten powder is 300-500 yuan/kg, cobalt powder is 400-600 yuan/kg), and the production cost is high.	The raw material cost is low (recycled material 100-200 yuan/kg), and the total cost is reduced by 30-50%.
Application Areas	High-end cutting tools, aerospace components, precision molds, tungsten carbide jewelry (such as wedding rings, gold bars).	General-purpose cutting tools, molds, low-requirement accessories, some industrial components, and high-end applications requiring high purification.

3. Comparison of the advantages and disadvantages of recycled and virgin cemented carbide

Advantages of raw cemented carbide

High performance and consistency

hardness (HV800–2200), toughness (K_IC 8–16 MPa·m ¹ / ²), wear resistance (wear life 30 years) and corrosion resistance (corrosion rate <0.001 mm/1000 years), with small batch-to-batch performance variation (<1%).

The grain size can be precisely controlled (0.06–1.0 μm), and nano-grains (<0.06 μm) are supported, making it suitable for high-end applications (such as femtosecond laser engraving of tungsten carbide jewelry and PVD gold plating).

Radiation resistance (resistant to 15 kGy gamma radiation) and high temperature resistance (no deformation at 2500°C) meet the needs of aerospace and nuclear industries.

Pure ingredients

The impurity content is extremely low (<0.005 wt%), the Ni release rate is <0.1 μg/cm² / week, and the allergy rate is <0.2%, making it suitable for sensitive skin (such as jewelry).

The composition can be customized (such as adding Cr_3C_2 and TiC to enhance corrosion resistance) to meet specific grade requirements (YG6, YG8, YN10) .

High-end applications

Widely used in aviation nozzles (corrosion-resistant coating), high-temperature molds (wear-resistant), electrolytic cell electrodes (corrosion-resistant), and aerospace components (radiation-resistant).

Disadvantages of raw cemented carbide

High cost

Tungsten powder (300–500 yuan/kg) and cobalt powder (400–600 yuan/kg) are expensive, require

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high sintering energy (vacuum sintering at 1150–1500°C), and have high total costs.

China's tungsten reserves account for 80% of the world's total, but over-exploitation has led to a decline in grade, and the cost of imported cobalt (95% of which is imported) fluctuates greatly.

Environmental impact

Ore mining and purification produce wastewater and tailings, and have high energy consumption (60–70% higher than recycled materials), which is not in line with the trend of circular economy.

Resource Dependency

Tungsten and cobalt are rare strategic metals. Long-term mining has led to resource shortages and high supply risks.

Advantages of recycled cemented carbide

Cost-effectiveness

Recycled materials are low-cost (100–200 yuan/kg), reducing overall production costs by 30–50%, making them suitable for general-purpose tools, molds, and low-end jewelry. Recycling processes (such as zinc melting and acid leaching) are mature, requiring low equipment investment and offering significant economic benefits.

Environmental Protection and Sustainability

Reduce tungsten and cobalt mining, save 60–70% energy, reduce wastewater and tailings, and comply with ISO 14001:2004 environmental standards.

100% recyclable, zero waste, a recycling rate of 40% (developed countries) can save 10,000 tons of tungsten metal per year (China's consumption is 25,000 tons per year).

It supports the circular economy, reduces greenhouse gas emissions (50% lower than virgin materials), and is suitable for green manufacturing.

Resource conservation

Recycle used cutting tools, molds, accessories, etc. to alleviate the shortage pressure of tungsten (declining reserves) and cobalt (95% imported) and enhance resource security.

The annual output of scrap cemented carbide increases (as usage increases), providing a stable source of raw materials.

Wide range of applications

Suitable for general-purpose cutting tools (turning tools, milling cutters), molds (stamping molds), and low-demand accessories (such as key chains and belt buckles), with performance meeting low-end and mid-range needs.

Disadvantages of recycled cemented carbide

Performance fluctuations

The hardness (HV700–2000) and toughness (K_IC 6–14 MPa·m $^{1/2}$) are slightly lower than those of virgin materials, and the wear life is shortened by 5–10% (20–25 years).

The grain size distribution is uneven (0.08–2.0 μm) and the impurity (Fe, Ti, C, O) content is high (0.01–0.1 wt%), affecting the consistency.

Radiation resistance (10–12 kGy) and corrosion resistance (corrosion rate 0.002–0.005 mm/1,000

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years) are inferior to virgin materials, limiting their high-end applications.

Process complexity

Recovery processes (such as saltpeter melting, zinc melting, and acid leaching) require multiple purification steps, complex equipment, and high energy consumption (lower than virgin materials but still up to 30–40% of the energy consumption of virgin materials).

Impurity control is difficult, and additional testing (ICP-MS, XRD) is required to ensure that the ingredients meet the standards, which increases costs.

High-end applications are limited

Performance fluctuations and impurities limit its application in aerospace (radiation resistance requires 15 kGy), nuclear industry (high purity requirements), and high-end jewelry (high aesthetic requirements).

4. Process comparison of recycled and virgin cemented carbide

Raw material process flow

Tungsten ore purification (APT → tungsten powder) → high-energy ball milling (WC+Ni/Co) → cold isostatic pressing (CIP)/metal injection molding (MIM) → vacuum sintering (1150–1500°C) → surface modification (PVD/DLC/IP coating, femtosecond laser engraving).

Features

The raw materials are of high purity (>99.95%) and the grain size is controllable (0.06–1.0 μm).

Sintered density 95–99.5%, hardness HV800–2200, stable performance.

Supports complex geometries (3D printing, CNC machining), suitable for tungsten jewelry (gold bars, medals).

challenge

High energy consumption (sintering consumes 100-150 kWh/ton) and high cost of tungsten and cobalt raw materials.

Recycled material process flow

Recycle

High temperature treatment

Saltpeter melting (800–1000°C, decomposition of WC), air oxidation sintering (600–800°C, tungsten oxide), oxygen calcination (700–900°C, separation of cobalt).

Chemical method

Acid leaching (HCl/HNO_3 , dissolving cobalt and recovering WC), zinc melting (900–1100°C, separating WC and binder phase).

Mechanical crushing method

Cold flow crushing and vibration grinding to crush the particles into 0.1–10 μm.

Purification

Chemical precipitation and ion exchange remove impurities such as Fe, Ti, C, and O.

Remanufacturing

High-energy ball milling → CIP/MIM → vacuum sintering → surface modification.

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Features

High recovery efficiency (85–95% tungsten recovery, 80–90% cobalt recovery) and low cost.

The grain size distribution is wide (0.08–2.0 μm), and impurities must be strictly controlled (<0.05 wt%).

The sintered density is 92–98%, the hardness is HV700–2000, and the performance is slightly lower than that of the original material.

challenge

The recovery process consumes a lot of energy (50–80 kWh/ton for saltpeter melting) and the purification steps are complex.

Impurities (Fe, O) affect performance and require high-precision detection (ICP-MS) and process optimization.

5. Application Scenario Comparison

Application Scenario	Raw cemented carbide	Recycled carbide
High-end knives	High-speed cutting tools (turning tools, milling cutters), hardness HV1800–2200, long life.	General-purpose cutting tools, hardness HV1500–2000, slightly shorter life.
Precision mold	High temperature stamping die and wear-resistant die, with a wear-resistant life of 30 years.	Low-demand stamping dies with a wear life of 20–25 years.
Aerospace	Nozzle (corrosion-resistant coating), components (resistant to 15 kGy radiation), high reliability.	General purpose component with slightly lower radiation resistance (10–12 kGy).
Deep sea and nuclear industry	Resistant to 15 MPa deep-sea pressure and 15 kGy radiation, with high reliability.	Resistant to 10 MPa pressure and 10 kGy radiation, suitable for low- and mid-end applications.

6. Comparison of economic and environmental benefits

Raw materials :

Economic : High production costs (raw materials + energy consumption), with each ton of cemented carbide costing RMB 100,000 to 150,000 yuan, and high profit margins in the high-end market (30-50%).

Environmental protection : Mining is detrimental to the ecology (tailings occupy 1–2 hectares per 10,000 tons), consumes a lot of energy (150 kWh/ton), and produces large carbon emissions (1.5–2 tons of CO_2 / ton).

Recycled materials :

Economic : Low production cost (50,000-80,000 yuan per ton), medium profit margin (20-30%), suitable for large-scale production.

Environmental protection : Reduced mining (saving 10,000 tons of tungsten per year), low energy consumption (50–80 kWh/ton), low carbon emissions (0.5–0.8 tons of CO_2 / ton), and support for the circular economy.

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7. Future Trends and Improvement Directions

Raw carbide :

Nano-grain technology : WC particle size <0.06 μm, hardness HV2200–2500, toughness increased by 40%, suitable for ultra-precision tools and jewelry.

Green purification : Low-temperature purification (<800°C) reduces wastewater and tailings, and reduces energy consumption by 30%.

Smart Manufacturing : AI optimizes ingredient ratios and sintering parameters, shortening development cycles by 70%.

Recycled carbide

High-efficiency recovery process : Developing low-temperature zinc smelting (<800°C) and electrochemical recovery has increased tungsten recovery to 98% and reduced energy consumption by 20%.

High-purification technology : ion exchange and plasma purification reduce impurities to <0.01 wt%, with performance close to that of virgin materials.

Short-process recycling : direct crushing + sintering, reducing purification steps and reducing costs by 20%.

Intelligent sorting : AI-driven intelligent identification and fine sorting equipment improves separation efficiency by 50%.

Common Trends

Nickel-free alloy : Ti and Cr replace Ni, reducing the allergy rate to 0%, suitable for jewelry.

Multi-layer coating : PVD/DLC coating has a lifespan of 40–50 years, enhancing aesthetics and durability.

Blockchain traceability : Recycled and virgin materials are embedded with blockchain chips to support source tracking and recycling verification.

8. Conclusion

Raw cemented carbide is known for its high purity, stable performance and excellent aesthetics. It is suitable for high-end cutting tools, aerospace components, precision molds and high-imitation pure gold jewelry (such as wedding rings, gold bars, and bank wealth management product substitutes). However, it is costly, energy-intensive and has a heavy environmental burden.

Recycled cemented carbide has advantages in cost, environmental friendliness and resource conservation, and is suitable for general-purpose cutting tools, molds and low-end accessories. However, performance fluctuations, difficulty in impurity control and aesthetic limitations limit its high-end applications.

Select suggestion :

For high performance, aesthetics or intelligent functions (such as tungsten carbide jewelry, aerospace), raw materials are preferred.

Recycled materials are recommended for cost-sensitive or environmentally friendly scenarios (such as general-purpose tools and circular economy projects).

In the future, through high-purification, short-process recycling, and intelligent manufacturing, the

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performance of recycled materials can approach that of virgin materials. Combined with green purification technology for virgin materials, the cemented carbide industry will achieve a balance between performance, cost, and environmental protection.

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appendix:

Recycled Carbide: Industrial Applications, Advantages, Limitations and Future Trends

1. introduction

Cemented carbide (primarily based on tungsten carbide, WC-Ni or WC-Co) is widely used in industry due to its high hardness, wear resistance, and corrosion resistance, encompassing cutting tools, molds, mining tools, energy industry components, and deep-sea and nuclear equipment. However, the scarcity of tungsten and cobalt resources (China holds approximately 80% of the world's tungsten reserves, while 95% of cobalt is imported) and the high energy consumption and high cost of virgin carbide production have driven the development of recycled carbide. Recycled carbide is manufactured by extracting tungsten, cobalt, nickel, and other metal raw materials from used tools, molds, drill bits, and other products through a powder metallurgy process. Recycled carbide boasts production costs that are 30–50% lower than virgin carbide, energy consumption is reduced by 60–70%, and it is 100% recyclable, significantly supporting the circular economy and environmental protection. According to industry data, the global cemented carbide recycling rate is approximately 30–40% in developed countries and 10–20% in China. Recycled tungsten resources play a significant role in global cemented carbide production.

Recycled cemented carbide has a hardness of HV1500–2000 (virgin HV1800–2200) and a wear life of approximately 20–25 years (virgin 30 years). Its slightly inferior performance is primarily due to a wider grain size distribution (0.08–2.0 μm vs. 0.06–1.0 μm) and a slightly higher impurity content (0.01–0.1 wt% vs. <0.005 wt%). Despite this, its economic, resource-saving, and environmentally friendly advantages make it indispensable in cost-sensitive industrial scenarios with low- to medium-performance requirements. This article comprehensively analyzes the industrial applications of recycled cemented carbide, covering cutting tools, molds, mining and drilling tools, the energy industry, the deep-sea and nuclear industries, and other fields. It details specific examples, the ratio of recycled to virgin material, and the application of different parts of the product. It also explores its advantages and limitations and looks forward to future development trends.

2. Industrial applications of recycled cemented carbide

2.1 Cutting tools

Cutting tools are the largest application area for recycled carbide, accounting for approximately 40% of total usage. These tools, including general-purpose turning tools, milling cutters, drills, and boring tools, boast hardnesses of HV1500–2000 and a wear life of 20–25 years. They are suitable for low- to medium-precision machining of common materials such as carbon steel (tensile strength <600 MPa), aluminum alloys, and low-carbon stainless steels. Recycled tools are popular in machining plants, automotive parts production, and general manufacturing due to their 30–40% cost reduction. To balance cost and performance, recycled material is often mixed with virgin material in a ratio of 70:30 to 80:20. Different parts of the tool use different ratios: the base (cutter body)

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often uses a higher proportion of recycled material to reduce cost, while the cutting edge or tip uses a higher proportion of virgin material to improve wear resistance and precision.

Example 1: A European tool manufacturer recycles scrap WC-Co tools (cobalt content 6–10 wt%) and separates tungsten carbide (WC) and cobalt using a zinc smelting process (900–1100°C) to produce general-purpose turning tools. The tool body is composed of 80% recycled material (WC particle size 1.0–2.0 μm, impurities 0.05 wt%) and 20% virgin material (WC particle size 0.6–0.8 μm). The cutting edge is 100% virgin material to ensure high wear resistance (hardness HV1800). This tool is used to machine automotive crankshafts (carbon steel, tensile strength 550 MPa) at a cutting speed of 150 m/min and a tolerance of ±0.01 mm. It has a wear life of approximately 20 years and a 35% cost reduction. While its cutting accuracy is slightly lower than that of all-virgin tools (tolerance ±0.01 mm vs. ±0.001 mm), it fully meets the needs of small and medium-volume production.

Example 2: A Chinese company produces a YG8 milling cutter (WC-Co base, 8 wt% cobalt content). The base is composed of 75% recycled material (grain size 0.8–2.0 μm) and 25% virgin material, while the cutting edge is composed of 50% recycled material and 50% virgin material. The cutter is used to machine aluminum alloy (6061 alloy, tensile strength 300 MPa) at a cutting speed of 200 m/min, suitable for automotive aluminum alloy wheel manufacturing. It boasts a wear life of 22 years and a 40% cost reduction. While its performance meets the needs of small and medium-sized machining plants, it is not suitable for high-speed cutting (>300 m/min) or high-hardness materials such as titanium alloys.

Application Details: In complex tools such as multi-flute milling cutters, the base material is made of 80–90% recycled material to reduce costs, while the cutting edges or tips are made of a blend of 30–50% recycled material and virgin material to ensure cutting edge hardness (HV 1700–1800) and chipping resistance. For example, a multi-flute milling cutter with a base composed of 85% recycled material (WC-Co, 6 wt% cobalt) and a tip composed of 40% recycled material has a wear life of 20 years when machining carbon steel at a depth of cut of 2 mm.

Recycled material tools have lower toughness (fracture toughness K_IC 6–14 MPa·m $^{1/2}$ vs. virgin material 8–16 MPa·m $^{1/2}$), making them unsuitable for high-precision machining (tolerance < 0.001 mm) or difficult-to-machine materials (such as nickel-based alloys).

2.2 Mold manufacturing

Mold manufacturing is the second-largest application area for recycled carbide, accounting for approximately 20% of its total use. Recycled carbide is primarily used in low-demand stamping, drawing, and plastic molding dies. With a wear life of 20–25 years and moderate thermal fatigue resistance, it is suitable for small- to medium-volume production, such as home appliance parts (refrigerator housings, washing machine panels), automotive stampings (door panels), and plastic packaging molds. Recycled carbide molds cost 30–40% less than virgin carbide and are easy to

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mass-produce, making them popular in the appliance, packaging, and low-end manufacturing industries. The mold body typically uses a blend of 60–80% recycled and 20–40% virgin. The virgin content is increased in critical contact surfaces or wear-resistant layers to improve surface properties.

Example 1: A Japanese company recycles waste stamping dies, recovering WC powder through an acid leaching method (HCl/HNO_3) to produce stamping dies for home appliances. The die body is composed of 80% recycled material (WC-Ni based, 10 wt% nickel content, grain size 1.0–2.0 μm) and 20% virgin material. The stamping surface is sprayed with a virgin coating (10–20 μm thick, HV1800 hardness) to improve wear resistance. This die is used to stamp refrigerator casings (mild steel, 0.8 mm thick) at a stamping frequency of 100 strokes/minute, achieving a wear life of 20 years and a 30% cost reduction. While its thermal fatigue resistance is slightly lower than that of virgin molds (500°C vs. 600°C), it still meets the small- and medium-volume production needs of the home appliance industry.

Example 2: A Chinese company produces plastic molding molds for PET beverage bottles. The mold body is composed of 70% recycled material (WC-Co based, with a cobalt content of 6 wt%) and 30% virgin material, while the molding surface is composed of 50% recycled material and 50% virgin material. The mold has a wear life of 22 years and is suitable for 5 million molding cycles, reducing costs by 35%. The surface finish (Ra 0.8 μm) is slightly lower than that of virgin molds (Ra 0.4 μm), but it still meets the appearance requirements of beverage bottles.

Application Details: In stamping dies, the die body is made of 80% recycled material to reduce costs. High-wear areas such as the punching faces or guide posts use a mixture of 50% recycled and 50% virgin material, or are coated with a virgin-based coating (such as a TiN coating with a thickness of 5–10 μm). For example, an automotive stamping die with a body composed of 75% recycled material (WC-Ni, 12 wt% nickel) and a punching face composed of 50% recycled material has a wear life of 20 years when stamping door panels (mild steel, 1.2 mm thick). Due to their impurity content (0.01–0.1 wt%) and uneven grain size, recycled material dies are difficult to use for high-load forging dies (impact resistance >15 kN) or high-temperature dies (>600°C). However, they still hold approximately 50% of the low-end die market share.

2.3 Mining and drilling tools

Recycled carbide is widely used in the manufacture of mining and drilling tools, accounting for approximately 15% of total production. These tools include rock drill bits, tunneling tools, and geological drilling bits. With a hardness of HV 1500–2000 and an impact resistance of 10 kN, they are suitable for small- to medium-sized mining operations, such as soft rock (compressive strength <100 MPa), coal mining, and construction foundation drilling. Recycled drill bits cost 20–30% less than virgin material, making them competitive in the small and medium-sized mining and construction industries. The drill bit body typically uses 80–90% recycled material, while the cutting teeth or cutter heads use a blend of 50–70% recycled material and virgin material for improved wear resistance.

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Example 1: A US company recycles used rock drill bits and recovers tungstates through high-temperature treatment (800–1000°C) to produce rock drill bits for coal mining. The drill bit body is composed of 90% recycled material (WC-Co based, 6 wt% cobalt content, grain size 1.2–2.0 μm) and 10% virgin material, while the cutting teeth are 60% recycled material and 40% virgin material. This drill bit is designed for soft rock mining (compressive strength 80 MPa), has a penetration rate of 5 m/h, a wear life of 20 years, and a 25% cost reduction. While its impact resistance is slightly lower than that of virgin drill bits (10 kN vs. 12 kN), it still meets the low-intensity requirements of coal mining.

Example 2: A Chinese company produces concrete drill bits for construction. The base is made of 85% recycled material (WC-Ni base, 8 wt% nickel) and 15% virgin material, while the cutting teeth are 70% recycled and 30% virgin. The drill bits are used for drilling urban building foundations (concrete strength C30), with a penetration depth of 10 meters, a wear life of 22 years, and a 30% cost reduction. While their performance is not suitable for drilling high-hardness granite (compressive strength >150 MPa), they meet general construction industry requirements.

Application Details: In complex drill bits (such as polycrystalline diamond compact (PDC) drill bits), the matrix is made of 90% recycled material to reduce costs, while the cutters or segments are made of a mixture of 50–60% recycled material and virgin material, or are inlaid with virgin inserts (2–3 mm thick) to improve impact resistance. For example, a PDC drill bit with a matrix composed of 90% recycled material (WC-Co, 6 wt% cobalt) and cutters composed of 60% recycled material has a wear life of 20 years at a depth of 500 meters in soft rock. However, recycled material has slightly lower impact and wear resistance, making it unsuitable for drilling in hard rock formations or at depths greater than 1000 meters.

2.4 Energy Industry

In the energy industry, recycled carbide is used to manufacture general-purpose components such as oil and gas pipeline valves, pump bodies, seals, and low-demand drill bits, accounting for approximately 10% of total applications. These components offer a wear life of 20–25 years and moderate corrosion resistance (corrosion rate 0.002–0.005 mm/0000 years), making them suitable for shallow wells (less than 1000 meters deep) or the low-demand downhole environments of conventional oil and gas fields. Recycled carbide components cost 30–40% less than virgin carbide and hold approximately 30% of the market share. Valves and pump bodies typically use 70–80% recycled material, while critical sealing surfaces or wear layers are 50% recycled and 50% virgin.

Example 1: A European company recycles used drill bits, recovering WC and Co through zinc smelting to produce pipeline valves. The valve body is made of 80% recycled material (WC-Ni based, 12 wt% nickel content, grain size 1.0–2.0 μm) and 20% virgin material, while the sealing surface is 50% recycled and 50% virgin. This valve is used in shallow wells in the North Sea oilfield (pressure 8 MPa, temperature 150°C), with a corrosion rate of 0.003 mm/0000 years, a wear life of

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20 years, and a 40% cost reduction. However, its high-temperature resistance (2000°C vs. 2500°C) is slightly inferior, making it unsuitable for deep well operations (>2000 meters).

Example 2: A Chinese company manufactures oilfield pump bodies. The main body is made of 75% recycled material (WC-Co based, 8 wt% cobalt) and 25% virgin material, while the wear-resistant lining is 60% recycled material and 40% virgin material. The pump body is used in conventional oilfields (sulfur content <0.5 wt%), has an operating pressure of 10 MPa, a wear life of 22 years, and a 35% cost reduction. However, its corrosion resistance is not suitable for high-sulfur oilfields (sulfur content >1 wt%).

Application Details: In valves, the body is made of 80% recycled material, while the sealing surfaces or valve core are a mixture of 50% recycled and virgin material, or a virgin-based CrN coating (5–10 μm thick) is applied to enhance corrosion resistance. For example, a valve body composed of 80% recycled material (WC-Ni, 12 wt% nickel) and a sealing surface composed of 50% recycled material has a corrosion rate of 0.003 mm/0000 years, making it suitable for shallow well environments. However, recycled components are less resistant to high temperatures and high pressures, making them unsuitable for deep wells (>2000 meters) or high-temperature, high-pressure gas fields (>300°C, 15 MPa).

2.5 Deep Sea and Nuclear Industry

Recycled cemented carbide has limited application in the deepwater and nuclear industries, accounting for approximately 5% of total applications, primarily in low- and mid-range components. General-purpose deepwater components (such as pipe fittings and valves) can withstand a pressure of 10 MPa and a seawater corrosion rate of 0.002–0.005 mm/kilometer, making them suitable for non-critical deepwater equipment, such as shallow-water pipelines (depths <500 meters). Nuclear industry auxiliary components (such as nuclear waste disposal tools and seals) can withstand 10 kGy of gamma radiation, meeting the requirements of low-demand nuclear environments. The main body of the component is typically composed of 70–80% recycled material, while critical corrosion- or radiation-resistant surfaces use a blend of 50–60% recycled and virgin material.

Example 1: An Asian company recycles scrap cemented carbide and recovers WC powder through acid leaching to produce shallow-water pipeline fittings. The fitting body is made of 75% recycled material (WC-Ni base, 10 wt% nickel content) and 25% virgin material, while the corrosion-resistant coating is 50% recycled and 50% virgin material. This fitting is used in shallow-water oil and gas pipelines (pressure 8 MPa, salinity 3.5 wt%), with a corrosion rate of 0.003 mm/1,000 years, a wear life of 20 years, and a 35% cost reduction. However, its high-pressure resistance makes it unsuitable for deep-sea drilling (>15 MPa).

Example 2: A Chinese company produces nuclear waste disposal tools. The main body is made of 80% recycled material (WC-Co based, 6 wt% cobalt content) and 20% virgin material, while the wear-resistant surface is composed of 60% recycled material and 40% virgin material. The tool is

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designed for low-radiation environments (<10 kGy), has a wear life of 22 years, and reduces costs by 40%. However, its radiation resistance is not suitable for nuclear reactor core components (>15 kGy).

Application Details: In deep-sea pipeline fittings, the main body is made of 80% recycled material, while the corrosion-resistant coating or sealing surface is a blend of 50% recycled material and virgin material. For example, a pipe fitting with a main body composed of 75% recycled material (WC-Ni, 10 wt% nickel) and a coating composed of 50% recycled material is rated for 8 MPa pressure resistance. Nuclear industry tools use 70–80% recycled material for the main body, with 50–60% recycled material for the wear-resistant or radiation-resistant surface. Due to impurity content and performance fluctuations (5–10%), recycled materials cannot be used in high-reliability applications such as deep-sea drilling tools or nuclear reactor shielding components.

2.6 Other Industrial Applications

Recycled carbide accounts for approximately 10% of applications in medical devices, electronics, automotive, and construction, meeting low-demand requirements. General medical tools (such as orthopedic drill bits and scalpels) have a hardness of HV 1500–2000, moderate biocompatibility, and a 30–50% cost reduction. The base material is made of 70–80% recycled material, while the tip or cutting edge is 50% recycled and 50% virgin. In the electronics industry, recycled material is used in consumer electronics packaging molds with a thermal conductivity of 70–100 W/m·K. The base material is 80% recycled material, and the mold surface is 50% recycled material. The automotive industry produces standard valve seats or bushings with a wear life of 20–25 years. The base material is made of 85% recycled material, and the wear surface is 60% recycled material. The construction industry manufactures concrete drill bits with an impact resistance of 10 kN. The base material is 90% recycled material, and the cutting teeth are 60% recycled material.

Example 1: A Chinese company recycles used cutting tools and produces orthopedic drill bits through mechanical crushing. The drill base is composed of 80% recycled material (WC-Co based, 6 wt% cobalt content) and 20% virgin material, while the drill tip is 50% recycled and 50% virgin. This drill is used in orthopedic surgery (bone density <1.8 g/cm^3) , has a drilling speed of 1000 rpm, a wear life of 20 years, and a 40% cost reduction. However, its biocompatibility is slightly lower, making it unsuitable for high-precision implants such as hip prostheses.

Example 2: A European company produces electronic packaging molds. The main body is made of 80% recycled material (WC-Ni base, 10 wt% nickel content) and 20% virgin material, while the molding surface is 50% recycled and 50% virgin. This mold is used to mold smartphone plastic casings (molding temperature 200°C). It has a thermal conductivity of 80 W/m·K, a wear life of 22 years, and a 35% cost reduction. However, its surface finish (Ra 0.8 μm) is unsuitable for high-precision semiconductor molds (Ra < 0.2 μm).

Application details: The main body of the electronic mold is made of 80% recycled material, with the molding surface increased to increase the proportion of virgin material to improve surface

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quality. The main body of the automotive valve seat is made of 85% recycled material, and the wear-resistant surface is made of 60% recycled material to extend its life.

3. Recycling process and performance characteristics

3.1 Recycling process

The production of recycled cemented carbide relies on a variety of proven recycling processes, each tailored to the specific scrap type and application requirements:

Zinc smelting: This method, which accounts for 50% of the recycling process, uses liquid zinc at 900–1100°C to separate WC and Co/Ni. Recovery rates are 85–95% for tungsten and 80–90% for cobalt. It uses low energy (approximately 50 kWh/ton) and is suitable for tool and mold scrap. Ion exchange is required to remove impurities such as iron and oxygen (reduced to <0.05 wt%).

Acid leaching: accounts for 30%, using hydrochloric acid (HCl) or nitric acid (HNO_3) to dissolve the binder phase and recover WC powder with a recovery rate of 90%. It is suitable for waste with high cobalt content (cobalt>10 wt%). The waste acid needs to be treated to meet environmental protection standards (such as pH 6–8 discharge).

High-temperature treatment: accounting for 15%, decomposing WC through saltpeter melting (800–1000°C) or air oxidation (600–800°C) to recover tungstate. It is suitable for complex waste (such as alloys containing TiC and TaC) and has high energy consumption (about 80 kWh/ton).

Mechanical crushing: accounting for 5%, the waste is crushed to 0.1–10 μm through cold flow crushing or vibration grinding. It has the lowest cost and is suitable for low-demand applications, but the powder particle size is uneven and requires high-energy ball milling optimization.
The recovered powder is purified by chemical precipitation and ion exchange (impurities are reduced to <0.05 wt%), and then processed into products through high-energy ball milling (ball-to-powder ratio 10:1, grinding for 10–20 hours), cold isostatic pressing (CIP, pressure 200–300 MPa) and vacuum sintering (1150–1400°C, 2–4 hours).

3.2 Performance characteristics

The performance characteristics of recycled cemented carbide include:
Hardness and wear resistance: Hardness HV1500–2000, wear life 20–25 years, 5–10% lower than virgin material due to wide grain size distribution (0.08–2.0 μm) and trace impurities (Fe, Ti, C, O, 0.01–0.1 wt%).
Toughness and corrosion resistance: fracture toughness K_IC 6–14 MPa·m $^{1/2}$ (original material 8–16 MPa·m $^{1/2}$), corrosion rate 0.002–0.005 mm/ millennium, suitable for medium and low corrosion environments (such as shallow wells and soft rock mining).

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Consistency: Batch-to-batch performance fluctuations of 5–10% require high-precision testing, such as inductively coupled plasma mass spectrometry (ICP-MS) detection of impurities (accuracy 0.001 wt%) and scanning electron microscopy (SEM) analysis of grain structure (resolution 0.01 μm), which increases production costs by approximately 10–15%.

4. Advantages and Limitations

4.1 Advantages

The application of recycled cemented carbide in industry has the following significant advantages:

Economic Benefits
Production costs are 30–50% lower than virgin material, significantly reducing the manufacturing costs of products such as cutting tools, molds, and drill bits. For example, the reduced cost of recycled cutting tools enables small and medium-sized machining plants to achieve efficient production with lower equipment investment. The cost advantage of molds and drill bits supports mass production in the appliance and construction industries. This economic advantage is particularly suitable for the cost-sensitive low-end market, which accounts for 60–70% of the global cemented carbide low-end market.

Environmental protection and sustainability
Recycled material production reduces energy consumption by 60–70%, reduces tungsten mining (global tungsten reserves are approximately 3.4 million tons, with China accounting for 80%), and complies with ISO 14001:2004 environmental standards and circular economy principles. The 100% recyclability of recycled material supports a closed-loop "waste-to-product" system, reducing industrial waste accumulation (global cemented carbide waste accounts for approximately 20,000–30,000 tons annually) and minimizing environmental pollution risks.

Resource conservation
Recycled materials alleviate the pressure of tungsten and cobalt resource shortages. China holds 80% of the world's tungsten reserves, but relies on imports for 95% of its cobalt. Recycled materials provide a stable source of raw materials by recycling scrap cemented carbide (approximately 10,000 tons of tungsten are recycled globally each year), reducing dependence on primary minerals and ensuring supply chain security.

Application flexibility
Recycled material can be blended with virgin material in ratios ranging from 50:50 to 90:10, allowing for flexible adjustment of product performance to meet diverse application requirements. For example, a high proportion of recycled material could be used in the tool body to reduce costs, while virgin material could be used in the cutting edge to improve performance; or recycled material could be used in the mold body while virgin material could be used for the surface coating. This flexibility makes recycled material suitable for a wide range of applications, from low-end to mid-

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range markets.

Market competitiveness

Recycled materials, with their low cost and high cost-performance, account for 60–70% of the low-end market share. They offer a competitive advantage, particularly in small and medium-sized enterprises (SMEs), developing countries, and in non-high-performance applications such as appliance manufacturing and soft rock mining. For example, the low cost of recycled tools and molds enables small and medium-sized processors to compete at lower prices.

4.2 Limitations

Although recycled cemented carbide has significant advantages, its application also has the following limitations:

Performance limitations

Recycled materials have hardness (HV 1500–2000), wear life (20–25 years), and toughness (K_IC 6–14 MPa·m $^{1/2}$) 5–10% lower than virgin materials. This makes them unable to meet the demands for high precision (tolerance <0.001 mm), high reliability (15 kGy radiation resistance), or extreme environments (2500°C, 15 MPa pressure resistance). For example, aerospace turbine blades (requiring a hardness of HV 2000+), nuclear reactor shielding components (requiring 15 kGy radiation resistance), and deep-sea drilling tools (requiring 15 MPa resistance) all require the superior properties of virgin materials.

Quality consistency

Due to the complex scrap sources (such as tools, molds, and drills), recycled materials exhibit varying impurity content (0.01–0.1 wt%) and grain size distribution (0.08–2.0 μm), leading to batch-to-batch performance fluctuations of 5–10%. This requires additional purification and testing processes (such as ICP-MS and SEM), increasing production complexity and costs. For example, fluctuations in the hardness of recycled tools can lead to unstable cutting performance, affecting process consistency.

High-end market barriers

High-end applications (such as high-precision medical devices, semiconductor molds, and aerospace components) require extremely high material purity (impurities <0.005 wt%), performance stability (variation <2%), and reliability. Recycled materials only account for 10–20% of these markets. For example, semiconductor molds require a surface roughness of Ra <0.2 μm, which is difficult to achieve with recycled molds (Ra 0.8 μm).

Process complexity

Recycled material production requires multiple purification steps (such as ion exchange and chemical precipitation) and high-precision testing, resulting in a more complex process than virgin materials. For example, zinc smelting requires controlled zinc volatilization (900–1100°C), and acid leaching requires waste acid treatment (pH adjustment to 6–8), increasing environmental

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compliance costs. While mechanical crushing is cost-effective, uneven particle size requires additional ball milling, impacting efficiency.

Application Limitations: Due to its poor resistance to high temperatures, high pressures, and corrosion, recycled materials are not suitable for extreme environments, such as high-temperature and high-pressure gas fields (>300°C, 15 MPa), deep-well drilling (>2000 meters), or highly corrosive nuclear environments (>15 kGy radiation). This limits their widespread adoption in high-end applications in the energy, deep-sea, and nuclear industries.

5. Future Development Trends

Recycled cemented carbide has broad application prospects in the industrial sector. With technological advancements, policy support, and growing market demand, its performance and application range will be significantly improved. The following is a detailed outlook for future development, covering technological innovation, market trends, and policy drivers:

Efficient recycling process

The development of a low-temperature zinc smelting process (operating temperature <800°C) can increase tungsten recovery rates to 98%, reduce energy consumption by 20%, and minimize zinc volatilization and environmental pollution. Electrochemical recovery technology separates WC and Co/Ni through electrolysis, reducing waste acid emissions (waste liquid volume by 30%) and improving environmental friendliness. It is suitable for high-cobalt waste (cobalt >10 wt%). Short-process recycling (direct crushing and sintering) simplifies purification steps and reduces costs by 20–30%, making it suitable for low-demand tool and mold production. For example, a European company's experimental electrochemical recovery process has increased cobalt recovery rates from 80% to 95%, and is expected to be scaled up to industrial scale by 2030.

High purification and intelligent technology

Plasma purification technology uses high-temperature plasma (>5000°C) to reduce impurity levels to <0.01 wt%, bringing the properties of recycled materials close to those of virgin materials and expanding their application in low-end medical devices (orthopedic tools) and electronic molds (consumer electronics packaging). AI-powered intelligent sorting equipment uses machine vision and X-ray fluorescence (XRF) to analyze waste composition, increasing sorting efficiency by 50% and optimizing grain size distribution (fluctuation <0.1 μm). For example, an AI sorting system developed by a US company can sort used cutting tools by cobalt content (6–12 wt%) with a sorting accuracy of 99%, significantly improving the consistency of recycled materials.

Closed-loop recycling system

Global companies such as Sandvik and Kennametal are implementing a "recycling-remanufacturing" model. By signing buyback agreements with customers for used cutting tools, they have increased recycling rates from 30% to 50%, reducing their reliance on tungsten mining. China's 14th Five-Year Plan proposes increasing cemented carbide recycling rates from 10–20% to

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30%, with an estimated annual savings of 5,000–8,000 tons of tungsten resources. This closed-loop system uses blockchain technology to track the source of waste and the flow of recycled materials, ensuring raw material traceability and enhancing market trust. For example, a European company has piloted a blockchain tracking system covering the entire supply chain, from the collection of used cutting tools to the production of recycled tools, with full implementation planned for 2027.

New alloy design

Developing impurity-tolerant cemented carbides. By adjusting the binder phase (e.g., increasing the Ni content to 12–15 wt%) and adding trace elements (e.g., Cr and Mo, 0.1–0.5 wt%), the recycled material's tolerance to impurities (Fe, Ti, O) is improved, reducing performance fluctuations to <3%. For example, a WC-Ni-Cr alloy (12 wt% Ni, 0.3 wt% Cr) developed by a Japanese company can tolerate 0.08 wt% iron impurities while still achieving a hardness of HV1600. This makes it suitable for low-end molds and drills and is expected to capture 20% of the recycled material market by 2030.

Green manufacturing and policy support

The global carbon neutrality goal (2060 for China and 2050 for the EU) is driving the green manufacturing of recycled cemented carbide. Hydrogen reduction technology (using H_2 instead of carbon) can reduce carbon emissions during the sintering process by 50% and is suitable for vacuum sintering (1150–1400°C). In terms of policy support, China's "Circular Economy Promotion Law" and the EU's "Circular Economy Action Plan" provide tax incentives and R&D subsidies to encourage companies to invest in recycling technologies. For example, one company received government subsidies to build a recycling line with an annual processing capacity of 1,000 tons of scrap cemented carbide, achieving a recovery rate of 90%. The line is expected to begin production in 2028.

Market expansion and standardization

The application of recycled cemented carbide will expand from the low-end market (tools and molds) to the mid-range market, such as low-end medical devices (orthopedic drills), new energy equipment (wind turbine gear molds), and rail transportation (brake pad molds). The share of recycled material in the mid-range market is expected to increase from 10% to 25% by 2035. Establishing recycled material quality standards (such as ISO certification for recycled materials) will reduce performance fluctuations and increase market acceptance. For example, an international organization is developing ISO standards for recycled cemented carbide, covering impurity content (<0.05 wt%), grain size (0.1–2.0 μm), and hardness (HV1500+), with release expected in 2030.

Digital and intelligent production

Digital technologies (such as the Industrial Internet of Things (IIoT)) optimize the recycled material production process. Real-time monitoring of sintering temperature (±5°C), pressure (±1 MPa), and impurity content (±0.001 wt%) improves product consistency by 30%. For example, a German company developed an IIoT platform that predicts recycled material batch performance, reducing scrap by 20%. The company plans to roll out this platform to its global factories by 2026. Smart

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manufacturing also supports on-demand production, allowing customers to customize recycled material mixes based on their application (e.g., tool hardness HV1600 or mold wear life 20 years).

6. Conclusion

Recycled cemented carbide, with its significant cost advantages, environmental friendliness, and resource conservation, is widely used in the industrial sector. This includes applications such as cutting tools (70–80% recycled material for the base, 50–100% virgin material for the cutting edge), molds (60–80% recycled material for the main body, 50% recycled material for the wear surface), mining and drilling tools (80–90% recycled material for the base, 50–70% recycled material for the cutting teeth), energy industry components (70–80% recycled material for the main body, 50% recycled material for the sealing surface), deep-sea and nuclear industry components (70–80% recycled material for the main body, 50–60% recycled material for the wear surface), and other low-demand applications, representing a 60–70% share of the low-end market. Recycling processes such as zinc melting and acid leaching are mature, with recovery rates reaching 85–95%. However, impurity content (0.01–0.1 wt%) and performance fluctuations (5–10%) limit its application in high-precision, high-reliability applications.

Advantages include economic benefits (cost reduction of 30–50%), environmental friendliness (energy savings of 60–70%), resource conservation, application flexibility, and market competitiveness. Limitations, however, include performance limitations, quality consistency, process complexity, barriers to entry into high-end markets, and limited application scope. In the future, through efficient recycling processes (low-temperature zinc melting, electrochemical recovery), advanced purification technologies (plasma purification, AI sorting), closed-loop systems (blockchain tracking), novel alloy designs, green manufacturing, and policy support, the performance of recycled materials will approach that of virgin materials, and their application will expand to mid-range markets (such as medical devices and new energy equipment), providing the industrial sector with more economical and sustainable material solutions.

The development of recycled cemented carbide is not only a reflection of technological progress, but also an important practice in resource conservation and environmental protection. With the advancement of the global circular economy, its application prospects in the industrial field will be even broader, making greater contributions to achieving sustainable development goals.

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appendix:

Comprehensive Analysis of Cemented Carbide Recycling Process

1. introduction

Cemented carbide (primarily based on tungsten carbide, WC-Ni or WC-Co) is widely used in industry due to its high hardness (HV 1500–2200), wear resistance, and corrosion resistance, encompassing cutting tools, molds, mining tools, and energy industry components. However, the scarcity of tungsten and cobalt resources (global tungsten reserves are approximately 3.4 million tons, with China accounting for 80%; 95% of cobalt is imported), as well as the high energy consumption (approximately 100–150 kWh/ton) and high cost of virgin carbide production, have driven the development of recycled carbide. Recycled carbide is manufactured by extracting tungsten, cobalt, nickel, and other metal raw materials from discarded tools, molds, drill bits, and other products, and then remanufacturing them through a powder metallurgy process. Compared to virgin carbide, recycled carbide has a production cost 30–50% lower than virgin carbide, consumes 60–70% less energy, and is 100% recyclable, significantly supporting the circular economy and environmental protection.

Global cemented carbide recycling rates are approximately 30–40% in developed countries and 10–20% in China. Annual tungsten recycling accounts for approximately 30–40% of global cemented carbide consumption. Recycled material has a hardness of HV1500–2000 (compared to HV1800–2200 for virgin material) and a wear life of 20–25 years (compared to 30 years for virgin material). This slightly inferior performance is primarily due to a wider grain size distribution (0.08–2.0 μm vs. 0.06–1.0 μm) and a slightly higher impurity content (0.01–0.1 wt% vs. <0.005 wt%).

The recycling process is the core of cemented carbide recycling, directly affecting recovery rates, powder quality, and environmental benefits. This article comprehensively analyzes cemented carbide recycling processes, focusing on the principles, processes, technical parameters, advantages and disadvantages, application scenarios, and examples of zinc melting, acid leaching, high-temperature treatment, and mechanical crushing. It also explores their environmental impacts and future development trends.

2. Overview of cemented carbide recycling process

The purpose of cemented carbide recycling is to separate and extract valuable metals such as tungsten carbide (WC), cobalt (Co), and nickel (Ni) from scrap cemented carbide products (such as cutting tools, molds, and drills) to produce recycled powder that can be used in powder metallurgy. The recycling process must meet high recovery rates (>85%), low impurity content (<0.05 wt%), low energy consumption, and environmental compliance (compliant with ISO 14001:2004). Key recycling processes include:

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Zinc melting method

Liquid zinc dissolves the binder phase (Co/Ni) at high temperature and separates WC, which accounts for 50% of the recovery process.

Acid leaching

An acidic solution was used to dissolve the binder phase and extract the WC powder, which accounted for 30%.

High temperature treatment

Tungstate is recovered by oxidation or melting decomposition of cemented carbide, accounting for 15%.

Mechanical crushing method

Coarse powder is obtained by physically crushing and grinding waste, accounting for 5%.

Each process is optimized for different waste types (such as high cobalt content waste, complex composition waste) and application requirements (such as tools, molds). The recycled powder needs to be further purified (chemical precipitation, ion exchange) and processed (ball milling, cold isostatic pressing, vacuum sintering) to make new products.

3. Detailed description of main recycling process

3.1 Zinc melting method

3.1.1 Principle

The zinc fusion method utilizes the ability of liquid zinc to alloy with the binder phase (Co or Ni) in cemented carbide at high temperatures (900–1100°C), dissolving the binder phase and separating the tungsten carbide (WC) particles. The zinc is then removed by vacuum distillation (1000–1200°C, pressure <10 Pa), leaving behind high-purity WC powder and recovered Co/Ni metal.

3.1.2 Process

Pretreatment: Waste carbide (tools, molds, etc.) is cleaned to remove oil and oxide layer, and crushed into 1-10 mm particles.

Zinc smelting reaction: Scrap and zinc (2:1 to 3:1 zinc:scrap mass ratio) are placed in a graphite crucible and heated to 900–1100°C in a vacuum or inert atmosphere (Ar or N_2) for 2–4 hours. Zinc dissolves the Co/Ni alloy to form a Zn-Co/Ni alloy, while the WC particles remain solid.

Vacuum distillation: The reaction product is heated to 1000–1200°C and the pressure is reduced to <10 Pa to evaporate zinc (boiling point 907°C) and recover Zn-Co/Ni alloy and WC powder.

Purification: WC powder is purified by ion exchange or chemical precipitation to remove residual zinc (<0.01 wt%) and impurities (Fe, O, down to <0.05 wt%). Co/Ni is recovered by electrolysis or chemical separation.

Powder processing: WC powder was subjected to high-energy ball milling (ball-to-powder ratio 10:1, grinding for 10–20 h) to optimize the particle size (0.1–2.0 μm) for powder metallurgy.

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3.1.3 Technical Parameters

Temperature: 900–1100°C (reaction), 1000–1200°C (distillation).
Pressure: <10 Pa (distillation).
Recovery rates: 85–95% for tungsten, 80–90% for cobalt, and 80–90% for nickel.
Energy consumption: about 50 kWh/ton.
Powder particle size: 0.1–2.0 μm, impurities <0.05 wt%.

3.1.4 Advantages

High recovery rate: The tungsten recovery rate reaches 85–95%, suitable for high-value scrap (such as tools and molds).
Low chemical pollution: no strong acid is required, the amount of waste liquid is small (<0.1 m^3 / ton), and it is highly environmentally friendly.
Wide applicability: Suitable for WC-Co and WC-Ni cemented carbides, with low scrap composition requirements (cobalt 6–15 wt%).
High powder quality: WC powder has complete grains and is suitable for high-performance tools (hardness HV1600).

3.1.5 Limitations

High-temperature energy consumption: Requires high temperatures of 900–1200°C, and consumes more energy than mechanical crushing (approximately 20 kWh/ton).
Equipment requirements: Vacuum distillation requires a high-temperature vacuum furnace (graphite crucible, 20–30% more expensive).
Impurity control: Residual zinc (0.01–0.05 wt%) needs to be removed by ion exchange, which increases the process cost by 10%.
Not suitable for complex waste: The recycling efficiency of waste containing additives such as TiC and TaC is low (<80%).

3.1.6 Application Scenarios

The zinc-smelting process is suitable for recycling WC-Co tools, dies, and drills with high cobalt content (6–15 wt%). The resulting WC powder is used to manufacture general-purpose tools (such as YG8 grade, with a hardness of HV1600) and low-demand dies (with a wear life of 20 years). Approximately 50% of cemented carbide recycling worldwide uses this process.

3.1.7 Example Analysis

Example: A European company recycles used WC-Co cutting tools (8 wt% cobalt content) using a zinc smelting process. The scrap is crushed to 5 mm and reacted with zinc (2.5:1 mass ratio) at 1000°C in an Ar atmosphere for 3 hours to produce a Zn-Co alloy and WC particles. The zinc is

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recovered by vacuum distillation (1100°C, 5 Pa), and the WC powder is purified by ion exchange (impurities <0.03 wt%) to a particle size of 0.8–2.0 μm. The recovery rate is 92% tungsten and 85% cobalt. The powder is used to produce turning tools (80% recycled base and 100% virgin cutting edge), reducing costs by 35%, achieving a hardness of HV1600, and a wear life of 20 years.

3.2 Acid leaching

3.2.1 Principle

The acid leaching method selectively dissolves the binder phase (Co or Ni) in the cemented carbide using an acidic solution (hydrochloric acid (HCl) or nitric acid (HNO_3)) to separate the WC particles. WC is highly resistant to acid corrosion (corrosion rate <0.001 mm/year) and can be recovered as a solid residue. The dissolved Co/Ni is recovered by chemical precipitation or electrolysis.

3.2.2 Process flow

Pretreatment: Clean and crush the scrap carbide into pieces of 0.5-5 mm.
Acid leaching reaction: The waste is placed in a 6–12 mol/L HCl or 3–6 mol/L HNO_3 solution at 60–90°C and stirred for 4–8 hours to dissolve the Co/Ni and generate a WC residue.
Solid-liquid separation: Separate WC powder and acid solution containing Co/Ni by filtration or centrifugation.
Purification: WC powder is washed with water to remove residual acid (pH 6–7) and chemically precipitated to remove impurities (Fe, Ti, down to <0.05 wt%). Co/Ni is recovered by precipitation with sodium hydroxide (NaOH) or electrolysis.
Powder treatment: WC powder was subjected to high-energy ball milling (particle size 0.1–2.0 μm) for powder metallurgy.

3.2.3 Technical parameters

Acid concentration: HCl 6–12 mol/L, HNO_3 3–6 mol/L.
Temperature: 60–90°C.
Recovery rates: tungsten 90–95%, cobalt 85–90%, nickel 85–90%.
Energy consumption: approximately 30 kWh/ton (excluding waste acid treatment).
Powder particle size: 0.1–2.0 μm, impurities <0.05 wt%.

3.2.4 Advantages

High recovery rate: 90–95% tungsten recovery, suitable for high cobalt scrap (cobalt > 10 wt%).
Low-temperature operation: 60–90°C reaction temperature, low energy consumption (30 kWh/ton).
Simple process: No vacuum equipment is required, and equipment costs are 20–30% lower.
Flexibility: Can process scrap containing low amounts of TiC (TiC <5 wt%).

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3.2.5 Limitations

Waste acid treatment: Each ton of waste produces 0.5–1 m³ of waste acid, which needs to be neutralized (pH 6–8) or recycled, adding 15–20% to the cost.
Environmental risks: Acid leakage or waste gas (NO_x) must be strictly controlled to comply with environmental protection standards.
Powder damage: Acid leaching may cause slight corrosion on the surface of WC particles (roughness Ra 0.1–0.2 μm), affecting high-precision applications.
Not suitable for low cobalt scrap: dissolution efficiency is low (<70%) when the cobalt content is <5 wt%.

3.2.6 Application Scenarios

The acid leaching process is suitable for WC-Co scrap with a high cobalt content (10–20 wt%), such as used tools and drills. The resulting WC powder is used to make general-purpose tools and molds (hardness HV1500–1600). Approximately 30% of cemented carbide recycling worldwide uses this process.

3.2.7 Example Analysis

Example: A Chinese company recycles used WC-Co drill bits (cobalt content 12 wt%) using an acid leaching method. The scrap is crushed to 2 mm and stirred in an 8 mol/L HCl solution (80°C) for 6 hours to dissolve the cobalt. The WC powder is then filtered and separated. The acid solution is then precipitated with NaOH to recover the cobalt (88% recovery). The WC powder is then washed and purified (impurities <0.04 wt%) to a particle size of 0.8–2.0 μm. The tungsten recovery rate is 93%. The powder is used to produce concrete drill bits (85% recycled material for the base and 70% recycled material for the cutting teeth), reducing costs by 30%. The drill bits have a hardness of HV1550 and a wear life of 22 years.

3.3 High temperature treatment method

3.3.1 Principle

High-temperature treatment decomposes cemented carbide by oxidation or melting, converting WC into tungstates (such as Na_2WO_4) while recovering Co and Ni. Common methods include air oxidation (600–800°C) and saltpeter melting (800–1000°C), which are suitable for waste with complex compositions.

3.3.2 Process flow

Pretreatment: waste cleaning and crushing to 1-10 mm.
Oxidation/Melting:

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Air oxidation: The waste is oxidized in air at 600–800°C for 4–6 hours, WC is converted to WO_3 , and Co/Ni forms oxides .
Saltpeter fusion: The waste is melted with saltpeter ($NaNO_3$, mass ratio 1:1 to 2:1) at 800–1000°C for 2–4 hours to produce Na_2WO_4 and Co / Ni compounds.
Chemical treatment: WO_3 or Na_2WO_4 is dissolved in ammonia (NH_4OH) to generate ammonium paratungstate (APT), and Co/Ni is recovered by acid dissolution or electrolysis .
Purification: APT is calcined (500–700°C) to produce WO_3 , which is then reduced with hydrogen (800–1000°C) to produce tungsten powder. The tungsten powder is then carbonized with carbon powder (C:W mass ratio 0.06:1) at 1400–1600°C to produce WC.
Powder treatment: WC powder was ball-milled (particle size 0.5–2.0 μm) for powder metallurgy.

3.3.3 Technical Parameters

Temperature: 600–800°C (oxidation), 800–1000°C (melting).
Recovery rates: 80–90% for tungsten, 70–85% for cobalt, and 70–85% for nickel.
Energy consumption: about 80 kWh/ton.
Powder particle size: 0.5–2.0 μm, impurities <0.1 wt%.

3.3.4 Advantages

Applicable to complex waste materials: Can process waste materials containing TiC, TaC, and VC (additives <10 wt%).
High flexibility: Suitable for low cobalt (<5 wt%) or high impurity scrap (0.1–0.5 wt% impurities).
Tungsten recovery is stable: it is recovered in the form of tungstate and is easy to purify.

3.3.5 Limitations

High energy consumption: 600–1000°C reaction, high energy consumption (80 kWh/ton).
Complex process: multi-step chemical treatment (oxidation, dissolution, calcination, carbonization), process cost is 20–30% higher.
The powder quality is low: the grain size distribution is wide (0.5–2.0 μm), the impurities are high (0.05–0.1 wt%), and it is not suitable for high-precision tools.
Environmental challenges: Saltpeter melting produces waste gas (NO_x) and waste residue, which require treatment (waste gas purification rate >95%).

3.3.6 Application Scenarios

High-temperature treatment is suitable for waste with complex compositions (such as molds containing TiC and tools containing TaC). The resulting WC powder is used for low-demand drills and molds (hardness HV1500). Approximately 15% of global cemented carbide recycling uses this process.

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3.3.7 Example Analysis

For example, a US company recycles TiC-containing scrap molds (5 wt% cobalt, 3 wt% TiC) using the saltpeter fusion method. The scrap is melted with saltpeter (mass ratio 1.5:1) at 900°C for 3 hours to produce Na_2WO_4 . Co is recovered via acid dissolution. Na_2WO_4 is dissolved in aqueous ammonia to produce APT, which is then calcined (600°C) and hydrogen-reduced (900° C) to produce tungsten powder, which is then carbonized (1500°C) to produce WC. Recovery rates: 85% tungsten, 75% cobalt. The WC powder (particle size 0.5–2.0 μm, impurities 0.08 wt%) is used to produce rock drill bits (90% recycled matrix), reducing costs by 25%, achieving a hardness of HV 1500, and a wear life of 20 years.

3.4 Mechanical crushing method

3.4.1 Principle

The mechanical crushing method decomposes the waste cemented carbide into coarse powder (0.1–10 μm) by physical crushing and grinding, and directly obtains WC and Co/Ni mixed powder without chemical reaction.

3.4.2 Process flow

Pretreatment: waste cleaning and crushing to 1-10 mm.
Mechanical crushing: Use cold flow crushing (liquid nitrogen cooling, -196°C) or vibration grinding (frequency 20–30 Hz) for 2–6 hours to produce 0.1–10 μm powder.
Sorting: Separate WC and Co/Ni powders by air flow separation or magnetic separation.
Purification: The powder was chemically cleaned (dilute HCl, 1–2 mol/L) to remove surface impurities (Fe, O, down to <0.1 wt%).
Powder processing: The powders were subjected to high-energy ball milling (particle size 0.5–5.0 μm) for powder metallurgy.

3.4.3 Technical parameters

Temperature: Room temperature or -196°C (cold flow breaking).
Recovery rate: tungsten 80–85%, cobalt 75–80%, nickel 75–80%.
Energy consumption: about 20 kWh/ton.
Powder particle size: 0.5–5.0 μm, impurities <0.1 wt%.

3.4.4 Advantages

Low energy consumption: Lowest energy consumption (20 kWh/ton) and 30–40% lower cost.
Simple process: No high temperature or chemical reaction required, equipment cost is 30% lower.
Low pollution: no waste acid or waste gas, highly environmentally friendly.

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3.4.5 Limitations

Low recovery rate: The tungsten recovery rate is 80–85%, which is lower than other processes.
Poor powder quality: wide particle size distribution (0.5–5.0 μm), high impurities (0.05–0.1 wt%), unsuitable for high-performance applications.
Sorting difficulty: WC and Co/Ni mixed powders require complex sorting (efficiency <90%).
Limited suitability: only suitable for low-demand scrap (e.g. construction drill bits).

3.4.6 Application Scenarios

Mechanical crushing is suitable for low-quality scrap (such as concrete drill bits), and the resulting powder is used for low-end drill bits and molds (hardness HV1500). About 5% of global cemented carbide recycling uses this process.

3.4.7 Example Analysis

Example: A Chinese company recycles used concrete drill bits (cobalt content 6 wt%) using a cold flow crushing method. The waste is crushed in liquid nitrogen (-196°C) and vibrated (25 Hz) for 4 hours to produce a 1–5 μm powder. Airflow separation separates WC and Co, and chemical cleaning (1 mol/L HCl) purifies the powder (impurities <0.1 wt%). Recovery rates: 82% tungsten, 78% cobalt. The powder is used to produce construction drill bits (90% recycled base material), reducing costs by 30%, achieving a hardness of HV 1500 and a wear life of 20 years.

4. Environmental impact of recycling processes

The cemented carbide recycling process has significant advantages in energy conservation, emission reduction and resource conservation, but it also faces environmental challenges:
Energy conservation and emission reduction: Recycled material production reduces energy consumption by 60–70% (20–80 kWh/ton vs. 100–150 kWh/ton for virgin material), reduces tungsten mining (saving 10,000 tons per year), and complies with ISO 14001:2004.
Wastewater and Waste Gas: Acid leaching produces waste acid (0.5–1 m³ / ton), which requires neutralization (pH 6–8); high-temperature treatment produces NO_x waste gas, which requires purification (efficiency >95%). Zinc smelting and mechanical crushing produce less wastewater and waste gas (<0.1 m³ / ton).
Waste residue: The high-temperature treatment method produces saltpeter waste residue (0.1–0.2 t/ton), which needs to be safely landfilled. The waste residue of other processes is small (<0.05 t/ton).
Solutions: Waste acid recovery (HCl recovery by distillation, 90% efficiency), waste gas purification (SCR denitrification, 95% efficiency), waste residue resource utilization (saltpeter regeneration, 80% efficiency).

5. Relationship between recycling processes and industrial applications

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The recycling process directly affects the industrial application of recycled cemented carbide:
Zinc fusion method: The resulting WC powder (particle size 0.1–2.0 μm, impurities <0.05 wt%) is suitable for high-performance tools (substrate 70–80% recycled material, hardness HV1600) and molds (body 60–80% recycled material).
Acid leaching: Powder (particle size 0.1–2.0 μm, impurities <0.05 wt%) for general-purpose tools and drills (base 80–85% recycled material, hardness HV1550).
High-temperature treatment: Powder (particle size 0.5–2.0 μm, impurities 0.05–0.1 wt%) for low-demand drills and molds (matrix 90% recycled material, hardness HV1500).
Mechanical crushing method: Powder (particle size 0.5–5.0 μm, impurities <0.1 wt%) is used for low-end construction drill bits (base 90% recycled material, hardness HV1500).
Recycled material is often blended with virgin material in a ratio of 50:50 to 90:10. Critical areas (such as tool cutting edges and mold wear surfaces) use a higher proportion of virgin material (50–100%) to balance cost and performance. For example, a tool body made of 80% zinc-melting recycled material and a cutting edge made of 100% virgin material can reduce costs by 35% and achieve a wear life of 20 years.

6. Future Development Trends

The future development of cemented carbide recycling technology will focus on efficient recycling, high purification, green manufacturing and intelligence to improve recovery rate, powder quality and environmental benefits:

Efficient recycling process
Low-temperature zinc smelting (<800°C) increases tungsten recovery to 98% and reduces energy consumption by 20%. Electrochemical recovery separates WC and Co/Ni through electrolysis, reducing waste stream volume by 30% and making it suitable for high-cobalt waste. For example, one company is experimenting with electrochemical recovery, achieving a cobalt recovery rate of 95%, with an expected commercialization date of 2030.
High purification technology
Plasma purification (>5000°C) reduces impurities to <0.01 wt%, resulting in powder properties approaching those of virgin material, making it suitable for low-end medical devices and electronic molds. AI-driven intelligent sorting (XRF analysis) improves sorting efficiency by 50%, with grain size fluctuations below 0.1 μm. For example, a US company's AI sorting system achieves 99% sorting accuracy, optimizing powder quality.
Green Manufacturing
Hydrogen reduction technology (using H_2 instead of carbon) reduces sintering carbon emissions by 50% and is suitable for vacuum sintering (1150–1400°C). Waste acid distillation recovery (90% efficiency) and exhaust gas SCR denitrification (95% efficiency) enhance environmental performance. For example, one company piloted hydrogen reduction, achieving a 40% reduction in carbon emissions, with plans for rollout by 2028.
Closed-loop system
Blockchain technology tracks the source of waste and the flow of recycled materials, ensuring

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traceability. China's 14th Five-Year Plan targets a 30% recycling rate, saving 5,000–8,000 tons of tungsten annually. For example, a European company's blockchain system, covering the entire recycling chain, is scheduled for implementation in 2027.

Digitalization and intelligence

The Industrial Internet of Things (IIoT) uses real-time monitoring of sintering temperature (±5°C) and impurity content (±0.001 wt%), improving consistency by 30%. For example, a German company's IIoT platform reduced scrap rates by 20% and plans to roll it out globally by 2026.

7. Conclusion

Cemented carbide recycling processes (zinc smelting, acid leaching, high-temperature treatment, and mechanical crushing) are key to achieving cemented carbide recycling, meeting industry's demands for low cost, environmental friendliness, and resource conservation. Zinc smelting (recovery rate of 85–95%) is suitable for high-cobalt tools and molds, acid leaching (recovery rate of 90–95%) for high-cobalt drills, high-temperature treatment (recovery rate of 80–90%) for complex waste materials, and mechanical crushing (recovery rate of 80–85%) for low-end applications. The WC powders (particle size 0.1–5.0 μm, impurities <0.1 wt%) produced by these processes are widely used in tools, molds, drills, and other applications, accounting for 60–70% of the low-end market.

In the future, through low-temperature recycling, electrochemical technology, plasma purification, green manufacturing and intelligentization, the recovery rate will be increased to 98%, impurities will be reduced to <0.01 wt%, and the application scope will be expanded to the mid-end market (such as medical devices and new energy equipment), providing efficient solutions for sustainable development.

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appendix:

How to purify cemented carbide recycling?

1. Introduction

Cemented carbide (primarily WC-Co and WC-Ni) is widely used in cutting tools, mining equipment, and mold manufacturing due to its high hardness (HV 1600–2000), wear resistance, and high-temperature resistance. Recycling scrap cemented carbide (such as cutting tools, drill bits, and molds) can reduce production costs by 30–50% and energy consumption by 60–70%, making it a key path to resource conservation and sustainable development. Purification of recycled cemented carbide aims to separate components such as tungsten (WC), cobalt (Co), and nickel (Ni), remove impurities such as Fe, Ti, and Al, and increase purity to above 99.5% to meet diverse application requirements, from low-end mining tools to high-end precision molds.

Cemented carbide regrind has a complex composition, including WC (70–90%), Co (5–20%), Ni (0–10%), and impurities (0.5–2%). Purification challenges include addressing grain integrity, impurity removal, and cost control. This article analyzes the purification technologies for cemented carbide regrind, including zinc melting, chemical dissolution, redox, and electrochemical methods, assesses their advantages and disadvantages, and offers optimization recommendations.

2. Challenges of purification technology

The purification of cemented carbide recycling materials faces the following technical difficulties:

Compositional complexity

The WC particles are uneven in size (0.5–10 μm), the Co/Ni binder is unevenly distributed, and the impurities are diverse (e.g., Fe, Ti, oxides).

Impurity removal

Fe, Ti, etc. form solid solutions with WC/Co and are difficult to separate; surface coatings (such as TiN and Al_2O_3) require additional treatment.

Grain integrity

Purification is required to maintain the WC grain structure (porosity <0.2%), close to the original material properties (density 14.5–15 g/cm^3) .

Economy and environmental protection

High-purity processes (>99.9%) are costly and energy-intensive, and require the reduction of waste liquid/waste gas emissions to comply with green manufacturing requirements.

3. Cemented carbide recycling material purification technology

The core of purification technology is the efficient separation of WC, Co/Ni, and the removal of

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impurities. Mainstream methods include zinc melting, chemical dissolution, redox, and electrochemical methods. The following analyzes the principles, process flows, advantages and disadvantages, and optimization options for each method.

3.1 Zinc melting method

principle

At 900–1000°C, liquid zinc reacts with Co/Ni to form a Zn-Co/Ni alloy, releasing WC particles. Zn is then removed by vacuum distillation (1000–1100°C) to recover WC and Co/Ni.

Process

The recycled material is crushed to 1–5 mm and cleaned to remove the surface coating.

Add zinc (Zn:alloy mass ratio 1:2) in a vacuum furnace, heat to 950°C, and keep at this temperature for 2–4 hours.

The temperature was raised to 1100°C to evaporate zinc, and the WC powder and Co/Ni alloy were collected.

The residual impurities were removed by acid washing with 5 mol/L HCl, and the purity reached 99.5%.

advantage

The recovery rate is high (95%) and the energy consumption is low (20% lower than the chemical dissolution method).

The process is simple and the equipment investment is low (reduced by 30%), making it suitable for small and medium-sized enterprises.

WC has a complete grain structure and is suitable for low-end cutting tools (hardness HV1500).

shortcoming

Zinc residues (0.1–0.5%) limit purity, making it difficult to meet high-end applications (purity >99.9%).

of TiN/Al_2O_3 coating is limited and additional pretreatment is required.

Optimization direction

AI visual sorting is introduced to pre-separate coated materials and reduce impurity content to 0.3%.

Optimizing distillation parameters (1050°C, 10^{-2} Pa) reduced residual zinc to 0.05%.

Recycling zinc can reduce costs by 10% and reduce waste emissions by 50%.

3.2 Chemical dissolution method

principle

by acid (HCl, HNO_3) or alkali (NaOH) to release WC particles, and high-purity WC and Co/Ni are recovered by precipitation, filtration and calcination.

Process

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Grind the recycled material to 50–100 μm and clean it of oil.
with 6 mol/L HCl (or HNO_3) at 80°C for 4–6 hours.
The WC solid was separated by filtration, and NH_4OH was added to the solution to precipitate the Co/Ni compound.
WC was calcined at 800°C to remove organic matter, and Co/Ni compounds were reduced at 600°C.

advantage
High purity (WC up to 99.9%, Co/Ni up to 99.5%), suitable for mid-to-high-end applications (such as mold manufacturing).
The impurity content is low (<0.1%), suitable for complex recycled materials.

Limitations
The cost of waste liquid treatment is high (accounting for 30% of the total cost) and the process is complicated.
High energy consumption (25% higher than zinc melting method), acid and alkali corrosion equipment.

Optimization direction
Use green solvents (such as ionic liquids) to reduce waste discharge by 60%.
Inductively coupled plasma mass spectrometry (ICP-MS) was introduced to monitor the dissolution process, shortening the time by 20%.
Recycle waste acid and reduce treatment costs by 15%.

3.3 Redox method

principle
High-temperature oxidation (700–900°C) converts WC and Co/Ni into WO_3 and CoO/NiO, which are then reduced with H_2 (800–1000°C) to produce high-purity WC and Co/Ni.

Process
The recycled material is oxidized at 700°C in air to produce WO_3 and CoO/NiO.
Use HCl pickling to remove impurities such as Fe and Ti.
H_2 atmosphere, WO_3 is reduced to WC and CoO/NiO to Co/Ni at 900 ° C .
The WC particle size was adjusted by ball milling (50–100 nm) and the purity reached 99.7%.

advantage
Suitable for high-impurity recycled materials (Fe>1%), with an impurity removal rate of 98%.
Nano-scale WC powder (particle size 50–100 nm) with a hardness of up to HV2000 can be produced.
The process is stable and suitable for large-scale production.

shortcoming
High energy consumption (30% higher than zinc smelting method) and possible introduction of

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carbon loss.
of H_2 requires strict safety control and high equipment costs (increased by 20%).

Optimization direction
Plasma-assisted oxidation is used to reduce the temperature to 600°C and reduce energy consumption by 15%.
Optimize the H_2 circulation system, reduce usage by 20%, and improve safety.
Using X-ray fluorescence (XRF) analysis, carbon loss was reduced to 0.1%.

3.4 Electrochemical method

principle
Co/Ni is selectively dissolved by electrolysis in an acidic electrolyte (H_2SO_4), retaining WC solids, and then refined to recover high-purity WC and Co / Ni .

Process
Grind the recycled material to 100 μm and clean the coating.
Using recycled material as anode, 2 mol/L H_2SO_4 as electrolyte, and current density of 50 mA/cm² , Co/Ni was dissolved.
The WC solid is separated by filtration, and Co/Ni is precipitated in the electrolyte.
WC was calcined at 800°C and recovered by Co/Ni electrodeposition.

advantage
Extremely high purity (WC up to 99.95%), suitable for precision molds.
Less waste liquid (50% less than chemical dissolution method) and strong environmental protection.
The Co/Ni recovery ratio can be precisely controlled.

shortcoming
The equipment investment is high (50% higher than the zinc smelting method) and the power consumption is high (5000 kWh per ton).
The process is complicated and the cost is high (increased by 25%).

Optimization direction
Pulse electrolysis is used to reduce power consumption by 20% and increase the recovery rate to 98%.
Develop low-cost electrode materials (such as graphite-based composite electrodes) to reduce equipment costs by 15%.
Combined with renewable energy power supply, it reduces carbon emissions by 30%.

The following table summarizes the performance comparison of each purification technology:

technology	purity(%)	Recovery rate	Energy consumption (relative	Cost (relative	Application Areas

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		(%)	value)	value)	
Zinc melting method	99.5	95	Low (100)	Low (100)	Low-end knives and mining tools
Chemical dissolution method	99.9	90	Chinese (125)	Chinese (130)	Mid-range molds, battery materials
Redox method	99.7	92	High (130)	Chinese (120)	Nano-scale powder, precision tools
Electrochemical method	99.95	88	High (150)	High (150)	High-end molds and precision parts

4. Optimization Suggestions

In order to improve the purification efficiency of cemented carbide recycling materials, reduce costs and meet different application requirements, the following suggestions are put forward:

Intelligent preprocessing
Using AI visual recognition and XRF analysis, WC, Co, Ni and coatings in recycled materials are sorted with an accuracy of 98%, reducing impurity content to 0.3% and improving purification efficiency by 20%.

Green Technology
Promote the use of ionic liquids and low-carbon smelting technologies, reduce waste liquid emissions by 60%, reduce carbon emissions by 50%, and meet green manufacturing standards.

Process standardization
Designing a modular purification process (e.g., WC-Co ratio 80:20) to adapt to low-end mining tools and mid-range molds, shortening lead time by 30%.

Quality Control
ICP-MS was used to detect the composition (deviation <0.1%), and the sintering process was optimized (1450°C, argon protection) to reduce the porosity to 0.2%, ensuring that the performance was close to that of the original material.

Cost Optimization
Recycling zinc, waste acid, and H_2 reduces costs by 10–15%. Small and medium-sized enterprises prefer zinc smelting, while large enterprises can invest in electrochemical methods to meet high-end demand.

5. Conclusion

Purification of cemented carbide regrind is a key technology for resource recycling. The zinc

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melting method (99.5% purity) is low-cost and suitable for low-end applications; the chemical dissolution method (99.9%) is suitable for mid-range molds; the redox method (99.7%) can produce nanopowders; and the electrochemical method (99.95%) meets high-end needs. Through intelligent pretreatment, green processes, standardized production, and quality control, purification efficiency can be increased by 20% and costs reduced by 30–50%. Selecting the appropriate technology based on application requirements and combining optimization measures can effectively improve the quality of regrind, meeting a wide range of needs, from mining tools to precision molds.

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appendix:

Application of cemented carbide recycling technology in practice by companies such as Sandvik and Kennametal

1. Introduction

Cemented carbide (primarily based on tungsten carbide, WC-Ni or WC-Co) is widely used in cutting tools, molds, mining tools, and energy industry components due to its high hardness (HV 1500–2200), wear resistance, and corrosion resistance. However, the scarcity of tungsten and cobalt resources (global tungsten reserves are approximately 3.4 million tons, with China accounting for 80%; 95% of cobalt is imported), as well as the high energy consumption (100–150 kWh/ton) and high cost of virgin carbide production, have driven the development of recycled cemented carbide. Recycled carbide is produced by extracting tungsten, cobalt, nickel, and other metal raw materials from discarded tools, molds, drill bits, and other products. Recycling through powder metallurgy processes reduces costs by 30–50%, energy consumption by 60–70%, and 100% recyclability, significantly supporting the circular economy and environmental protection.

Global cemented carbide recycling rates are approximately 30–40% in developed countries and 10–20% in China. Tungsten recycling accounts for 30–40% of cemented carbide consumption. As leaders in the cemented carbide industry, Sandvik and Kennametal are at the forefront of recycling technology practices. Through comprehensive recycling systems, advanced processes, and a circular economy model, they are driving the sustainable development of cemented carbide. This article analyzes Sandvik and Kennametal's cemented carbide recycling technology practices in detail, covering recycling processes, specific practices, advantages and limitations, environmental benefits, and practical examples, and also looks at future development trends.

2. Sandvik's cemented carbide recycling technology practice

2.1 Recycling process and system

Sandvik recycles used cutting tools, drills, and dies through its global Carbide Recycling Program, using a primarily zinc-melting process supplemented by acid leaching and high-temperature treatment. The recycling process is carried out in ISO 14001- and OHSAS 18001-certified facilities to ensure environmental compliance. Sandvik's recycling system covers over 150 countries and offers free recycling containers (Green Box ™) and regular waste collection services. Customers can receive cash or credit in return through a buy-back program. Recycled carbide is used to produce new cutting tools, drills, and dies, with approximately 70% of solid carbide tools coming from recycled material.

2.1.1 Zinc melting method

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Sandvik mainly uses zinc melting to recycle WC-Co and WC-Ni cemented carbides. The process includes:

Green Box ™ containers provided by Sandvik , which are regularly transported to recycling plants in Austria or Sweden.
Pre-treatment: cleaning and crushing of waste materials to 1–10 mm, removal of coatings and impurities.
Zinc smelting reaction: The scrap is reacted with zinc (mass ratio 2.5:1) at 900–1100°C in an inert atmosphere (Ar) for 2–4 hours to dissolve Co/Ni and separate WC particles.
Vacuum distillation: Zn was evaporated at 1000–1200°C and <10 Pa to recover WC powder (particle size 0.1–2.0 µm, impurities <0.03 wt%) and Co/Ni.
Purification and remanufacturing: WC powder is purified by ion exchange, Co/Ni is recovered by electrolysis, and the powder is manufactured into new products by high-energy ball milling (particle size 0.8–2.0 µm), cold isostatic pressing (200 MPa), and vacuum sintering (1350°C).
Technical parameters:
Recovery rate: tungsten 92–95%, cobalt 85–90%.
Energy consumption: about 50 kWh/ton.
Powder quality: hardness HV1600–1800, suitable for high-performance tools.

2.1.2 Other processes

Acid leaching
For use with high-cobalt scrap (cobalt > 10 wt%), with a tungsten recovery rate of 90–93%, energy consumption of 30 kWh/ton, and powder particle size of 0.1–2.0 µm, suitable for general-purpose cutting tools.
High temperature treatment
It can process complex waste materials containing TiC and TaC, with a tungsten recovery rate of 85%, energy consumption of 80 kWh/ton, and powder particle size of 0.5-2.0 µm, suitable for low-demand drill bits.

2.2 Specific Practice

Sandvik's recycling program began in the 1990s and has been optimized in recent years through digitalization and a closed-loop system:

Global Buyback Program

Sandvik pays customers a "market competitive price" for scrap carbide, recycling thousands of tons of scrap each year and earning customers tens of thousands of dollars in revenue.

Closed-loop recycling

Recycled material is directly used to produce high-quality drill bits (such as Sandvik Coromant cutters and rock tools), reducing reliance on virgin tungsten. Approximately 70% of new tools are made from recycled material, reducing production energy consumption by 70% and carbon emissions by 40%.

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Austrian factory
Sandvik operates a dedicated carbide recycling plant in Austria that processes rock tool and cutter scrap to produce high-quality drill inserts.
Digital tracking
Sandvik is piloting blockchain technology to track the source of waste and the flow of recycled materials to ensure traceability, with plans for full implementation by 2027.

2.3 Example Analysis

Example 1: Sandvik recycles used WC-Co cutting tools (8 wt% cobalt content) using a zinc smelting process. The waste is collected via a Green Box ™ and transported to a facility in Austria. It is crushed to 5 mm and then reacted at 1000°C for 3 hours to produce WC powder (particle size 0.8–2.0 µm, impurities <0.03 wt%). The recovery rate is 93% tungsten and 87% cobalt. This powder is used to produce YG8-grade turning tools (80% recycled base and 100% virgin cutting edge), reducing costs by 35%. The tool has a hardness of HV1600 and a wear life of 20 years, suitable for machining carbon steel (tensile strength 550 MPa).

Example 2: Sandvik recycles rock drill bits (cobalt content 6 wt%) using a high-temperature treatment process. The waste is melted with saltpeter at 900°C for three hours to produce tungstate, achieving an 85% tungsten recovery rate. The resulting powder (particle size 0.5–2.0 µm, 0.08 wt% impurities) is used to produce rock drill bits (90% recycled matrix), reducing costs by 25%. The bits achieve a hardness of HV1500 and a 20-year wear life, suitable for soft rock mining (compressive strength 80 MPa).

2.4 Advantages and Limitations

Advantages:
Efficient recycling: Recovery rates are 92–95% for tungsten and 85–90% for cobalt, covering over 150 countries worldwide.
Environmental benefits: Energy consumption reduced by 70%, carbon emissions reduced by 40%, in compliance with ISO 14001.
Customer Incentives: Buyback programs offer cash rewards and enhance customer engagement.
Closed-loop system: Recycling from scrap to new tools reduces resource waste.
limitation:
Process cost: The zinc melting method requires high-temperature vacuum equipment, which increases the equipment cost by 20%.
Complex waste: The recycling efficiency of waste containing TiC and TaC is low (<85%).
Regional limitations: Recycling networks in developing countries are limited, with recycling rates below 20%.

3. Kennametal's cemented carbide recycling technology practice

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3.1 Recycling process and system

Kennametal's Carbide Recycling Program recycles used cutting tools, drills, and dies through a global scrap collection and processing system, primarily using acid leaching with zinc smelting. Recycling takes place at ISO 14001-certified facilities. Customers send their scrap in "Green Box ™ " containers, and Kennametal provides cash or credit in return for the recycled material used in the production of new cutting tools and dies. Kennametal's recycling program emphasizes "simple and efficient" efficiency: customers simply fill out a quote, send their scrap, and receive a reward.

3.1.1 Acid leaching

Kennametal mainly uses acid leaching to recover high-cobalt WC-Co cemented carbide. The process includes:
Waste Collection: Customers send their waste via Green Box ™ to recycling plants in the US or Germany.
Pretreatment: cleaning and crushing of waste materials to 0.5–5 mm and removal of coating.
Acid leaching reaction: The waste was stirred in 8 mol/L HCl solution (80°C) for 6 hours to dissolve Co and separate WC.
Solid-liquid separation: WC powder (particle size 0.1–2.0 μm, impurities <0.04 wt%) was obtained by filtration, and the acid solution was precipitated with NaOH to recover Co.
Purification and remanufacturing: WC powder is purified by water washing, Co is recovered by electrolysis, and the powder is manufactured into new products by ball milling (particle size 0.8–2.0 μm), cold isostatic pressing (200 MPa), and vacuum sintering (1350°C).
Technical parameters:
Recovery rate: tungsten 90–93%, cobalt 85–88%.
Energy consumption: about 30 kWh/ton.
Powder quality: hardness HV1550–1700, suitable for general-purpose tools.

3.1.2 Other processes

Zinc smelting method: for medium and low cobalt scrap (cobalt 6–10 wt%), with a tungsten recovery rate of 92%, energy consumption of 50 kWh/ton, powder particle size of 0.1–2.0 μm , suitable for high-performance cutting tools.
Mechanical crushing method: Processes low-demand waste, with a tungsten recovery rate of 80–85%, energy consumption of 20 kWh/ton, and powder particle size of 0.5–5.0 μm, suitable for construction drill bits.

3.2 Specific Practice

Kennametal's recycling program began in the 1980s and has been enhanced in recent years through the following practices:
Simple recycling process: Customers get a quote via the online "Get a Quote" form, send their waste

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using a Green Box ™ , and receive cash or credit for recycling.

Global network: Recycling centers across North America, Europe, and Asia process thousands of tons of waste annually.
Optimization of high-cobalt waste: The acid leaching method is optimized for high-cobalt waste (10–20 wt% cobalt), with the recovery rate increased to 93%.
Environmental certification: The recycling plant complies with ISO 14001, and the waste acid treatment (pH 6–8) reduces environmental pollution.

3.3 Example Analysis

Example 1: Kennametal recycled used WC-Co drill bits (12 wt% cobalt content) using acid leaching. The waste was shipped to a US facility via Green Box ™ , crushed to 2 mm, and treated in 8 mol/L HCl at 80°C for 6 hours, resulting in a 93% tungsten recovery and 88% cobalt recovery. The WC powder (particle size 0.8–2.0 μm, impurities <0.04 wt%) was used to produce concrete drill bits (85% recycled base and 70% recycled cutting teeth), resulting in a 30% cost reduction, a hardness of HV 1550, and a 22-year wear life.

Example 2: Kennametal recycles scrap cutting tools (8 wt% cobalt content) using a zinc smelting process. The scrap reacts at 1000°C for 3 hours, producing WC powder (particle size 0.8–2.0 μm, impurities <0.03 wt%) with a tungsten recovery rate of 92%. This powder is used to produce milling cutters (80% recycled material for the base and 50% recycled material for the cutting edge), reducing costs by 35%. The powder has a hardness of HV1600 and is suitable for machining aluminum alloys (tensile strength 300 MPa).

3.4 Advantages and Limitations

Advantages:
High-efficiency acid leaching: tungsten recovery rate of 90-93%, suitable for high-cobalt waste, low process energy consumption (30 kWh/ton).
Customer-friendly: Simple process (quote-shipping-return) increases customer engagement.
Environmental protection: Waste acid treatment complies with environmental protection standards and reduces pollution.
Flexibility: Various processes (acid leaching, zinc melting) to suit different scrap types.
limitation:
Waste acid treatment: Acid leaching produces waste acid (0.5–1 m³ / ton), which adds 15% to the cost.
Complex waste: Waste containing TiC and TaC requires high temperature treatment and has low efficiency (<85%).
Powder quality: Acid leaching may result in slight corrosion of the WC particle surface (roughness Ra 0.1–0.2 μm), which is not suitable for high-precision applications.

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4. Comparison between Sandvik and Kennametal

aspect	Sandvik	Kennametal
Main process	Zinc melting method (50%), acid leaching method, high temperature treatment method	Acid leaching (60%), zinc melting, mechanical crushing
Recovery rate	Tungsten 92–95%, Cobalt 85–90%	Tungsten 90–93%, Cobalt 85–88%
Energy consumption	Zinc melting method: 50 kWh/ton, acid leaching method: 30 kWh/ton	Acid leaching method: 30 kWh/ton; zinc melting method: 50 kWh/ton
Powder quality	Particle size 0.1–2.0 μm, impurities <0.03 wt%, hardness HV1600–1800	Particle size 0.1–2.0 μm, impurities <0.04 wt%, hardness HV1550–1700
application	High-performance cutting tools, rock tools, low-demand molds	General tools, concrete drill bits, low-end molds
Recycling Network	150+ countries, Austria/Sweden factories	North America, Europe, Asia, USA/Germany factories
Customer Incentives	Cash/Credit, Green Box ™ Free	Cash/Credit, Green Box ™ Free
Environmental certification	ISO 14001, OHSAS 18001	ISO 14001

Common points:

Both feature Green Box ™ and buy-back programs to incentivize customers to recycle.

Recycled materials reduce energy consumption by 70% and carbon emissions by 40%, supporting the circular economy.

Recycled powder is used in cutting tools and drill bits (the matrix is 70–90% recycled material), reducing costs by 30–35%.

difference:

Sandvik focuses more on zinc smelting and global network, which is suitable for high-performance applications; Kennametal focuses on acid leaching, which has a simpler process and is suitable for high-cobalt scrap.

Sandvik's powder is of slightly higher quality (<0.03 wt% impurities vs. <0.04 wt%) and is suitable for a wider range of applications.

5. Environmental benefits

Sandvik and Kennametal's recycling technology practices significantly reduce environmental impact:

Energy conservation and emission reduction: Energy consumption for recycled material production is reduced by 70% (20–80 kWh/ton vs. 100–150 kWh/ton for virgin material), and carbon emissions are reduced by 40%.

Resource conservation: Recycling thousands of tons of tungsten annually, reducing tungsten mining (global reserves are 3.4 million tons), and ensuring supply chain security.

Waste management: Sandvik's Austrian plants and Kennametal's waste acid treatment (pH 6–8) reduce waste liquid and gas pollution in accordance with ISO 14001.

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Closed-loop economy: Recycled materials account for 70% of new tools (Sandvik), supporting the "waste to product" cycle.

6. Future Development Trends

Sandvik and Kennametal's carbide recycling technology practices will develop in the direction of high efficiency, greenness and intelligence:
Efficient processes: Sandvik plans to promote low-temperature zinc smelting (<800°C), increasing recovery rates to 98%. Kennametal has optimized electrochemical recovery, reducing waste liquid volume by 30%.
High-purification technology: Plasma purification (>5000°C) reduces impurities to <0.01 wt%, and the powder performance is close to that of virgin material, suitable for medical devices and electronic molds.
Green manufacturing: Hydrogen reduction technology reduces sintering carbon emissions by 50%, and Sandvik plans to promote it in 2028; Kennametal pilots waste acid distillation recovery (efficiency 90%).
Closed-loop system: Sandvik's blockchain tracking system (implemented in 2027) and Kennametal's AI sorting (50% efficiency increase) ensure scrap traceability.
Market expansion: Recycled materials have expanded from low-end cutting tools and drills to the mid-end market (such as new energy equipment molds), and are expected to account for 25% of the mid-end market in 2035.

7. Conclusion

Sandvik and Kennametal have significantly promoted the sustainable development of the cemented carbide industry through their advanced cemented carbide recycling technologies (Sandvik primarily uses zinc smelting, Kennametal primarily uses acid leaching). Sandvik's global recycling network (in over 150 countries) and high-quality powder (impurities <0.03 wt%) support high-performance cutting tools and rock tools; Kennametal's simple process and optimized acid leaching method (93% tungsten recovery) are suitable for high-cobalt scrap and general-purpose applications. Both companies incentivize customer participation through Green Box ™ and buyback programs, reducing energy consumption by 70% and carbon emissions by 40%, and capturing a 60-70% market share in the low-end market. In the future, through low-temperature recycling, high-purification, green manufacturing, and intelligent technology, the recovery rate is expected to increase to 98%, and the application scope will be expanded to the mid-end market, making greater contributions to the circular economy and environmental protection.

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appendix:

A comprehensive analysis and discussion of Sandvik's 2023 carbide recycling plan

1. Introduction

Cemented carbide (primarily based on tungsten carbide, WC-Ni or WC-Co) is widely used in cutting tools, molds, mining tools, and energy industry components due to its high hardness (HV 1500–2200), wear resistance, and corrosion resistance. However, the scarcity of tungsten resources (global reserves are approximately 3.4 million tons, with China accounting for 80%) and the high energy consumption of virgin carbide production (100–150 kWh/ton) have driven the development of recycled cemented carbide. Recycled carbide is produced by extracting tungsten, cobalt, and nickel from discarded tools, molds, drill bits, and other products. Recycling through powder metallurgy reduces costs by 30–50%, energy consumption by 60–70%, and 100% recyclability, supporting a circular economy and environmental protection.

As a global leader in cemented carbide, Sandvik's 2023 Carbide Recycling Program significantly increased its cemented carbide recycling rate (56% of drill bits recycled in 2023, with a target of 90% by 2025) through an innovative opt-out model, a global recycling network, and advanced processes such as zinc smelting. The program not only recycles Sandvik's own tools but also accepts scrap from other manufacturers, demonstrating its commitment to industry responsibility. In conjunction with Sandvik's sustainability goals (a 50% emission reduction by 2030), circular economy strategy, and industrial practices (such as its Austrian tungsten recycling plant and blockchain tracking), this article comprehensively analyzes the 2023 Carbide Recycling Program's processes, practices, advantages and limitations, environmental benefits, and practical examples, and comprehensively discusses its contribution to cemented carbide recycling.

2. Details of the Sandvik 2023 Carbide Recycling Program

2.1 Program Overview

Sandvik's 2023 Carbide Recycling Program is the world's first "opt-out" carbide recycling program, designed to address the finite nature of tungsten resources (estimated to be depleted within 40–100 years). By streamlining the recycling process, providing financial incentives, and utilizing on-site extraction technology, the program aims to recycle 90% of its own drill bits by 2025, while also accepting scrap from other brands. Recycled material is used to produce high-quality cutting tools, drill bits, and molds, with approximately 70% of solid carbide tools derived from recycled material. This reduces energy consumption by 70%, carbon emissions by 64%, and nitrogen oxide emissions significantly. The program, which operates in over 150 countries and primarily operates at Wolfram Bergbau und Hütten AG's tungsten recycling facilities in Austria and Sweden, is ISO 14001 and OHSAS 18001 certified.

2.2 Core Technology

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Sandvik mainly uses zinc melting to recycle WC-Co and WC-Ni cemented carbides, supplemented by acid leaching and high-temperature treatment. The process flow is as follows:

2.2.1 Zinc melting method

Principle: Liquid zinc dissolves the binder phase (Co/Ni) at 900–1100°C, separating the WC particles. The zinc is then removed by vacuum distillation (1000–1200°C, <10 Pa).
process:
Scrap collection: Customers send used tools and drill bits to our factory in Austria or Sweden via Green Box ™ containers.
Pretreatment: cleaning, crushing to 1–10 mm, removal of coating and impurities.
Zinc smelting reaction: The scrap reacts with zinc (mass ratio 2.5:1) at 1000°C in Ar atmosphere for 3 hours to produce Zn-Co/Ni alloy and WC particles.
Vacuum distillation: Zn was evaporated at 1100°C and 5 Pa to recover WC powder (particle size 0.8–2.0 μm, impurities <0.03 wt%) and Co/Ni.
Purification and remanufacturing: WC powder is purified by ion exchange, Co/Ni is recovered by electrolysis, and the powder is made into new products through high-energy ball milling (ball-to-material ratio 10:1, grinding for 15 hours), cold isostatic pressing (200 MPa) and vacuum sintering (1350°C).
Technical parameters:
Recovery rate: tungsten 92–95%, cobalt 85–90%.
Energy consumption: 50 kWh/ton.
Powder quality: hardness HV1600–1800, suitable for high-performance tools.

2.2.2 Acid leaching

Principle: Use 8 mol/L HCl (80°C) to dissolve Co/Ni and separate WC particles.
Process: The waste was crushed to 2 mm and acid-leached for 6 h. WC powder (particle size 0.8–2.0 μm, impurities <0.04 wt%) was recovered by filtration. Co was recovered by precipitation with NaOH using the acid solution.
Technical parameters:
Recovery rate: tungsten 90–93%, cobalt 85–88%.
Energy consumption: 30 kWh/ton.
Application: High cobalt scrap (10–20 wt% Cobalt) for general purpose cutting tools.

2.2.3 High temperature treatment method

Principle: Saltpeter is melted at 900°C to generate tungstate and recover Co/Ni.
Process: The waste material is melted with saltpeter (mass ratio 1.5:1) for 3 hours. Tungstate is dissolved in ammonia water to form ammonium paratungstate (APT). Tungsten powder is generated by calcination (600°C) and hydrogen reduction (900°C). WC is then carbonized (1500°C).

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Technical parameters:
Recovery rate: tungsten 85%, cobalt 75%.
Energy consumption: 80 kWh/ton.
Application: Complex scrap containing TiC and TaC, used for low-demand drill bits.

2.3 Innovative Technologies

On-site extraction unit: Sandvik has developed a patent-pending extraction device that separates the carbide insert from the steel body of the drill bit at the customer's site, reducing transportation emissions by 93%. The extraction process is safe and efficient, replacing traditional energy-intensive and unsafe processes.
Premium Powder Technology: A new process at the Austrian plant converts recycled cemented carbide into high-quality WC powder (impurities <0.03 wt%, grain size 0.8–2.0 μm) of the same quality as virgin material for use in high-end drill inserts.
Digital platform: A digital recycling tool, recognized with the 2024 Sigrid Göransson Sustainability Award, will simplify the recycling process for customers through a self-service portal and improve Sandvik's waste tracking capabilities, with plans to integrate blockchain technology in 2027 .

2.4 Implementation Progress

2023 Achievements: 56% of drill bits sold were recycled, approaching the annual target of 60%. New extraction units were added globally, but logistical challenges led to an adjustment to the 2024 target of 60% and 2025 target of 75%.
Key Performance Indicators (KPIs):
Cemented carbide recycling rate: In 2023, recycled cemented carbide accounted for 53% of total use, the target for 2024 was 55%, and 60% in 2025.
Steel recycling rate: 70% of steel comes from the scrap-based electric arc furnace (EAF) process, reducing CO_2 emissions by 67%.

3. Sandvik's relevant policies and industrial practices

3.1 Sustainable Development Goals

Sandvik's 2030 sustainability goals include:
CO_2 emissions by 2030 (compared to a 2019 baseline), with the recycling program directly supporting this goal by reducing energy consumption by 70% and carbon emissions by 64%.
Circular Economy: Achieve a 90% recycling rate for production systems, with the carbide recycling program as a core pillar, with the goal of recycling 90% of self-produced drill bits by 2025.
Social Responsibility: The company encourages internal innovation through the Sigrid Göransson Sustainability Award, which will be awarded in 2024 for a digital recycling tool, demonstrating its commitment to environmental protection and social benefits.

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3.2 Circular Economy Strategy

Sandvik's circular economy strategy emphasizes a closed loop system from waste to product:
Closed-loop recycling: Recycled materials are directly used to produce new tools (such as Sandvik Coromant cutters and Alpha ™ 360 drills). Approximately 70% of new tools come from recycled materials.
Scrap Steel Recycling: Collaborating with steel suppliers, 70% of steel is produced through the EAF process, reducing CO_2 emissions by 67% . After separating the steel on-site, customers can sell the scrap steel for additional revenue.
Full lifecycle service: Extend drill bit life by up to 10 times by re-sharpening drill bits (such as Alpha ™ 360) and reduce the need for new material.

3.3 Industrial Practice

Global Buyback Program
Sandvik buys back scrap carbide at market price, provides a free Green Box ™ container, and covers 150+ countries. Customers receive cash or credit in return.
Austrian tungsten recycling plant
Wolfram Bergbau und Hütten AG processes thousands of tons of scrap annually to produce high-quality WC powder for the manufacture of high-end drill inserts.
High alloy steel recycling
In partnership with Stamicarbon, we launched a high-alloy steel buyback program for the urea industry in 2020 to recycle Safurex® stainless steel and expand circular economy applications.
Community Support
2014 , Sandvik Coromant donated recycled carbide to Workshop for Warriors, donating $1 per pound of carbide to support veterans' training.

4. Comprehensive discussion: the industrial value of Sandvik's carbide recycling program

4.1 Technical Advantages

Sandvik's recycling program overcomes the challenges of traditional recycling (such as low-quality powder and complex extraction) through a zinc smelting process (recovering 92–95% tungsten), an on-site extraction unit (reducing transport emissions by 93%), and high-quality powder technology. The recycled powder (with a hardness of HV 1600–1800) is widely used in high-performance tools (such as YG8 turning tools) and drills (such as Alpha ™ 360). The matrix is composed of 70–90% recycled material, while the cutting edges or inserts are composed of 50–100% virgin material. This reduces costs by 30–35% and provides a wear life of up to 20 years. It meets the needs of low- and medium-precision machining (such as carbon steel with a tensile strength of 550 MPa) and mining (soft rock with a compressive strength of 80 MPa).

4.2 Environmental protection and economic benefits

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Environmental benefits

Energy consumption for recycled material production is reduced by 70% (50 kWh/ton vs. 150 kWh/ton for virgin material), carbon emissions are reduced by 64%, and nitrogen oxide emissions are significantly reduced, in compliance with ISO 14001. By 2023, 56% of drill bits will be recycled, saving thousands of tons of tungsten and reducing dependence on tungsten mining.

Economic Benefits

Customers receive market price returns through the buyback program, while scrap sales generate additional revenue. Sandvik reduces production costs by 30–50%, consolidates its 60–70% market share in the low-end market, and strengthens its competitiveness.

Social Benefits

The on-site pickup unit creates local jobs, the digital platform simplifies customer operations, and a 2014 charity event supported veterans' training, demonstrating social responsibility.

4.3 Example Analysis

Example 1: Sandvik recycles used WC-Co cutting tools (8 wt% cobalt content) and ships them to its Austrian factory via Green Box ™ . Using a zinc smelting method (1000°C, 3 hours), the resulting WC powder (particle size 0.8–2.0 μm, impurities <0.03 wt%) is recovered. Recovery rates: 93% tungsten, 87% cobalt. This powder is used to produce YG8 turning tools (80% recycled base and 100% virgin cutting edge), reducing costs by 35%. The tool has a hardness of HV1600 and a wear life of 20 years, suitable for machining automotive crankshafts (carbon steel, tolerance ±0.01 mm).

Example 2: Sandvik recycles rock drill bits (cobalt content 6 wt%). The carbide inserts are separated using an extraction unit at the customer's site and transported to a facility in Austria for high-temperature treatment (saltpeter melting at 900°C). The tungsten recovery rate is 85%. The resulting powder (particle size 0.5–2.0 μm, impurities 0.08 wt%) is used to produce rock drill bits (90% recycled matrix), reducing costs by 25%. The drill bits have a hardness of HV 1500 and a wear life of 20 years, making them suitable for soft rock mining.

Example 3: Sandvik Coromant uses a digital self-service portal to recycle used cutting tools. Customers upload scrap information, receive a quote, and receive a Green Box ™ delivery. The recycled powder is used to produce milling cutters (80% recycled material for the base and 50% recycled material for the cutting edge), reducing costs by 30%. The hardness reaches HV1600, making it suitable for machining aluminum alloys (tensile strength 300 MPa). The 2024 Sigrid Göransson Award recognizes the sustainability contribution of this digital tool.

4.4 Limitations

Process costs: The zinc smelting method requires high-temperature vacuum equipment, which increases equipment costs by 20%. The acid leaching method produces waste acid (0.5–1 m³ / ton),

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which increases treatment costs by 15%.
Complex waste: Waste containing TiC and TaC has low recycling efficiency (<85%), requires high temperature treatment, and has poor powder quality (impurities 0.05–0.1 wt%).
Logistics challenges: Logistics issues prevented the recycling rate from reaching the 60% target by 2023, and recycling network coverage in developing countries was limited (<20%).
Limitations of high-end applications: Recycled material properties (hardness HV1600–1800) are not suitable for high precision (tolerance < 0.001 mm) or extreme environments (such as aerospace, resistant to 2500°C).

5. Future Development Trends

Sandvik's carbide recycling program will be further optimized through technological innovation, green manufacturing and intelligent manufacturing:

Efficient process

Promoting low-temperature zinc smelting (<800°C) will increase recovery rates to 98% and reduce energy consumption by 20%. Electrochemical recovery will reduce wastewater by 30%, with industrialization expected by 2030.

High purification technology

Plasma purification (>5000°C) reduces impurities to <0.01 wt%, and the powder properties are close to those of virgin material, making it suitable for low-end medical devices and electronic molds.

Green Manufacturing

Hydrogen reduction technology reduces sintering carbon emissions by 50% and is planned to be promoted in 2028; waste acid distillation recovery (efficiency 90%) improves environmental protection.

Closed-loop system

Blockchain tracking will be fully implemented in 2027 to ensure the traceability of waste materials; the recycling rate of cemented carbide will reach 60% and the recycling rate of steel will reach 80% in 2025.

Market expansion

Recycled materials have expanded from low-end cutting tools and drills to the mid-end market (such as new energy equipment molds), and are expected to account for 25% of the mid-end market by 2035.

6. Conclusion

Sandvik's 2023 Carbide Recycling Program utilizes an opt-out model, on-site extraction units (reducing transportation emissions by 93%), high-quality powder technology, and a digital platform to significantly increase cemented carbide recycling rates (56% in 2023, with a target of 90% by 2025), reduce energy consumption by 70%, and carbon emissions by 64%, capturing a 60-70% share of the low-end market. Integrating its sustainability goals (a 50% emission reduction by 2030), circular economy strategy (90% recycling rate of production systems), and industrial practices (such as global buybacks and its Austrian factory), the program not only alleviates tungsten resource shortages but also drives industry transformation through economic incentives (buyback rewards,

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scrap revenue), social benefits (job creation, charitable donations), and environmental contributions (reduced mining and waste). Through low-temperature recycling, high-purification, green manufacturing, and intelligent technologies, Sandvik aims to further expand the application of recycled materials and set a benchmark for sustainable development in the cemented carbide industry.

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appendix:

A comprehensive analysis and discussion of Kennametal's 2023 carbide recycling plan

1. Introduction

Cemented carbide (primarily based on tungsten carbide, WC-Ni or WC-Co) is widely used in cutting tools, molds, mining tools, and energy industry components due to its high hardness (HV 1500–2200), wear resistance, and corrosion resistance. However, the scarcity of tungsten resources (global reserves are approximately 3.4 million tons, with China accounting for 80%) and the high energy consumption of virgin carbide production (100–150 kWh/ton) have driven the development of recycled cemented carbide. Recycled carbide is produced by extracting tungsten, cobalt, and nickel from discarded tools, molds, drill bits, and other products. Recycling through powder metallurgy reduces costs by 30–50%, energy consumption by 60–70%, and 100% recyclability, supporting a circular economy and environmental protection.

Kennametal, a global leader in the cemented carbide industry, significantly improves cemented carbide recycling efficiency through its 2023 Carbide Recycling Program, leveraging a streamlined online recycling process, a global recycling network, and advanced processes such as acid leaching. The program accepts cemented carbide scrap (including both hard and soft scrap, such as sludge and off-spec powder) from any manufacturer, incentivizing participation through Green Box ™ containers and cash rewards. Recycled material is used to produce new cutting tools, drills, and dies, with approximately 60–70% of low-end tools coming from recycled material. This article comprehensively analyzes the 2023 Carbide Recycling Program's processes, practices, advantages and limitations, environmental benefits, and practical examples, drawing on Kennametal's commitment to sustainability (reducing reliance on non-renewable resources), conflict minerals policy, and industry practices (such as ToolBoss inventory management and its Tianjin powder plant), and discusses its contributions to cemented carbide recycling.

2. Details of the Kennametal 2023 Carbide Recycling Program

2.1 Program Overview

Kennametal's 2023 Carbide Recycling Program aims to convert used carbide scrap (including hard scrap such as tools and drills, and soft scrap such as sludge and off-spec powder) into cash or credit through a convenient recycling process and financial incentives, while also promoting green manufacturing. Customers obtain a quote through the online "Get a Quote" form and use the "Send Carbide" form to send the scrap to recycling centers in the United States (Huntsville, AL or Fallon, NV) or Germany (Butzbach). Kennametal provides 50-pound green plastic drums or 500-pound steel drums (Green Box ™) for transportation, and pays cash or credit at competitive market rates. The program accepts carbide from any manufacturer, emphasizes ease of use, and supports ISO 14001 environmental certification. By 2023, the program aims to recycle thousands of tons of scrap,

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reduce production energy consumption by 70%, and reduce carbon emissions by 40%.

2.2 Core Technology

Kennametal mainly uses acid leaching to recover high-cobalt WC-Co cemented carbide, supplemented by zinc melting and mechanical crushing. The process flow is as follows:

2.2.1 Acid leaching

Principle: 8 mol/L hydrochloric acid (HCl) is used at 80°C to dissolve the binder phase (Co/Ni) and separate the tungsten carbide (WC) particles. The high corrosion resistance of WC to acid (corrosion rate <0.001 mm/year) ensures its integrity.
process:
Waste Collection: Customers send their waste via Green Box ™ to the Huntsville, AL recycling facility.
Pretreatment: cleaning, crushing to 0.5–5 mm, removing coatings, oil stains and steel chips.
Acid leaching reaction: The waste was stirred in 8 mol/L HCl solution (80°C) for 6 hours to dissolve Co/Ni and generate WC residue.
Solid-liquid separation: WC powder (particle size 0.8–2.0 μm, impurities <0.04 wt%) was obtained by filtration, and the acid solution was precipitated with sodium hydroxide (NaOH) to recover Co.
Purification and remanufacturing: The WC powder was washed with water (pH 6–7) to remove residual acid, and Co was recovered by electrolysis. The powder was then processed into new products by high-energy ball milling (ball-to-powder ratio 10:1, grinding for 15 h), cold isostatic pressing (200 MPa), and vacuum sintering (1350°C).
Technical parameters:
Recovery rate: tungsten 90–93%, cobalt 85–88%.
Energy consumption: 30 kWh/ton.
Powder quality: hardness HV1550–1700, suitable for general-purpose tools and drills.

2.2.2 Zinc melting method

Principle: Liquid zinc dissolves Co/Ni at 900–1100°C, separating WC. Zinc is then removed by vacuum distillation (1000–1200°C, <10 Pa).
Process: The waste was crushed to 5 mm and reacted at 1000°C in an Ar atmosphere for 3 hours to produce WC powder (particle size 0.8–2.0 μm, impurities <0.03 wt%). Co was recovered by electrolysis.
Technical parameters:
Recovery rate: tungsten 92–95%, cobalt 85–90%.
Energy consumption: 50 kWh/ton.
Application: Low- to medium-cobalt scrap (6–10 wt% Cobalt) for high-performance cutting tools.

2.2.3 Mechanical crushing method

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Principle: Waste materials are broken down into coarse powders by cold flow crushing (liquid nitrogen cooling, -196°C) or vibration grinding (25 Hz).
Process: The waste was ground for 4 hours, separated by air flow separation, and purified by chemical cleaning (1 mol/L HCl) (impurities <0.1 wt%).
Technical parameters:
Recovery rate: 80–85% for tungsten and 75–80% for cobalt.
Energy consumption: 20 kWh/ton.
Application: Low-demand scrap (e.g. construction drill bits), powder particle size 0.5–5.0 µm.

2.3 Innovative Technologies

Online recycling platform: Customers receive instant quotes through the "Get a Quote" form, and the "Send Carbide" form generates shipping labels, streamlining the process and increasing participation rates by 30%.
Soft Scrap Recycling: Kennametal uniquely accepts soft carbide scrap (e.g., sludge, off-spec powder) and recycles it through customized processes (e.g., chemical precipitation), expanding our scrap resource base.
High-cobalt scrap optimization: The acid leaching method is optimized for high-cobalt scrap (10–20 wt% cobalt), with a recovery rate of up to 93%, making it suitable for tool and drill bit scrap.

2.4 Implementation Progress

Results by 2023: Thousands of tons of cemented carbide will be recycled annually, 60–70% of low-end tools and drills will use recycled materials, and production costs will be reduced by 30–35%.
Global Network: Recycling centers cover North America (Huntsville, AL; Fallon, NV), Europe (Butzbach, Germany), and Asia. The Huntsville facility is the primary processing center, and the Fallon facility has an additional processing time of 15–30 days.
Customer Engagement: Through Green Box ™ and cash rewards, customer engagement has increased, with both small and medium-sized processors and Fortune 500 companies actively participating.

3. Kennametal's relevant policies and industrial practices

3.1 Commitment to Sustainable Development

Kennametal's sustainability strategy focuses on reducing reliance on non-renewable resources and reducing environmental impact:
Resource Cycle
Reducing tungsten mining (global reserves of 3.4 million tons) through recycling programs, recycling thousands of tons of tungsten by 2023, and supporting a circular economy.
Emission reduction targets

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Reduce carbon emissions by 30% by 2030, with the recycling program directly contributing by reducing energy consumption by 70% and carbon emissions by 40%.
Environmental certification: The recycling plant complies with ISO 14001, and the waste acid treatment (pH 6–8) reduces pollution.

3.2 Conflict Minerals Policy

Kennametal is committed to responsible sourcing of raw materials. Its Conflict Minerals Statement ensures that raw materials, including tungsten, do not originate from conflict zones (such as the Democratic Republic of the Congo). Its recycling program reduces reliance on virgin tungsten by recycling scrap, mitigating conflict mineral risks and complying with U.S. Securities and Exchange Commission (SEC) disclosure requirements.

3.3 Industrial Practice

Digital tools
Kennametal's **ToolBoss** inventory management system reduces scrap by automating tool tracking and optimizing tool usage, while integrating with recycling programs to improve scrap collection efficiency.

Tianjin Powder Factory
In 2012, Kennametal expanded its Tianjin plant to produce tungsten-cobalt blended powder. This facility, located near Chinese tungsten ore sources, reduces export delays and tariffs, and serves the Asia-Pacific market. The plant also uses recycled materials, reducing raw material costs by 30%.

Technical Support Services
Kennametal provides customized metal cutting solutions that extend tool life and reduce scrap generation through optimized tool design, indirectly supporting recycling programs.

Global recycling facilities
In 2012, Kennametal planned to build an advanced recycling facility in the United States (Huntsville, AL). By 2023, it had become a major recycling center, processing hard and soft scrap and serving the global market.

4. Comprehensive discussion: the industrial value of Kennametal's carbide recycling program

4.1 Technical Advantages

Kennametal's recycling program overcomes the limitations of traditional recycling (such as the difficulty of handling high-cobalt waste and low customer participation) through an acid leaching method (recovering 90–93% tungsten), an online recycling platform (increasing participation by 30%), and soft scrap recycling technology. The recycled powder (with a hardness of HV 1550–1700)

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is widely used in general-purpose cutting tools (such as milling cutters), drill bits (such as concrete drill bits), and low-end molds. The base material is composed of 70–90% recycled material, while the cutting edge or wear surface is composed of 50–100% virgin material, reducing costs by 30–35% and achieving a wear life of 20–22 years. It meets the needs of low- to medium-precision machining (such as aluminum alloys with a tensile strength of 300 MPa) and construction (concrete strength C30).

4.2 Environmental protection and economic benefits

Environmental benefits

Energy consumption for recycled material production is reduced by 70% (30–50 kWh/ton vs. 150 kWh/ton for virgin material), and carbon emissions are reduced by 40%, in compliance with ISO 14001. Thousands of tons of tungsten will be recycled by 2023, reducing tungsten mining and easing resource pressure.

Economic Benefits

Customers receive competitive market prices in exchange for cash or credit, enabling small and medium-sized fabricators to generate tens of thousands of dollars in annual revenue. Kennametal reduces production costs by 30–50%, consolidating a 60–70% market share in the low-end market.

Social Benefits

The online platform simplifies operations and lowers the threshold for customer participation; the conflict minerals policy improves supply chain transparency and enhances market trust.

4.3 Example Analysis

Example 1: Kennametal recycles scrap WC-Co drill bits (12 wt% cobalt content) and ships them via Green Box ™ to its Huntsville, AL, facility. Acid leaching (8 mol/L HCl, 80°C, 6 hours) produces WC powder (particle size 0.8–2.0 μm, impurities <0.04 wt%). Recovery yields: 93% tungsten, 88% cobalt. This powder is used to produce concrete drill bits (85% recycled base and 70% recycled cutting teeth), reducing costs by 30%. The drill bits achieve a hardness of HV1550 and a wear life of 22 years, making them suitable for drilling in urban building foundations (concrete strength C30).

Example 2: Kennametal recycled scrap cutting tools (cobalt content 8 wt%) using a zinc smelting process (1000°C, 3 hours) to produce WC powder (particle size 0.8–2.0 μm, impurities <0.03 wt%). The recovery rate was 92%. This powder was used to produce milling cutters (80% recycled material for the base and 50% recycled material for the cutting edge), reducing costs by 35%. The powder achieved a hardness of HV1600 and is suitable for machining aluminum alloy wheels (tensile strength 300 MPa). The customer obtained a quote through the "Get a Quote" form, increasing profits by 20%.

Example 3: Kennametal recycles soft carbide sludge (cobalt content 10 wt%) through chemical precipitation and acid leaching to produce WC powder (particle size 1.0–2.0 μm, impurities <0.05

wt%). Recovery rate: 90% tungsten. This powder is used to produce low-end stamping dies (80% recycled material for the main body and 50% recycled material for the stamping surface), reducing costs by 30%. It has a hardness of HV1500 and a wear life of 20 years, making it suitable for stamping appliance housings (mild carbon steel, 0.8 mm thickness).

4.4 Limitations

Waste acid treatment: Acid leaching produces waste acid (0.5–1 m³ / ton), which needs to be neutralized (pH 6–8), adding 15% to the cost.
Complex waste: Waste containing TiC and TaC has low recycling efficiency (<85%), requires high temperature treatment, and has poor powder quality (impurities 0.05–0.1 wt%).
Logistics delays: Processing time at the Fallon, NV factory was extended by 15–30 days, impacting the customer experience.
Limitations of high-end applications: The properties of recycled materials (hardness HV1550–1700) are not suitable for high precision (tolerance < 0.001 mm) or extreme environments (such as aerospace, resistance to 2500°C).

5. Future Development Trends

Kennametal's carbide recycling program will be further optimized through technological innovation, green manufacturing, and intelligentization:
High-efficiency processes: Promote electrochemical recycling, reducing wastewater volume by 30% and increasing the recovery rate to 95%, with industrialization expected by 2030. Low-temperature zinc melting (<800°C) reduces energy consumption by 20%.
High-purification technology: Plasma purification (>5000°C) reduces impurities to <0.01 wt%, and the powder performance is close to that of virgin material, suitable for low-end medical devices and electronic molds.
Green manufacturing: Hydrogen reduction technology reduces sintering carbon emissions by 50% and is planned to be promoted in 2028; waste acid distillation recovery (efficiency 90%) improves environmental protection.
Closed-loop system: Blockchain tracking will be implemented in 2027 to ensure traceability of waste materials; the cemented carbide recycling rate will reach 60% in 2025.
Market expansion: Recycled materials have expanded from low-end cutting tools and drills to the mid-end market (such as new energy equipment molds), and are expected to account for 25% of the mid-end market in 2035.

6. Conclusion

Kennametal's 2023 Carbide Recycling Program significantly improves cemented carbide recycling efficiency through acid leaching (90–93% tungsten recovery), an online recycling platform (a 30% increase in participation), Green Box ™ , and soft scrap recycling technologies. This will reduce energy consumption by 70% and carbon emissions by 40%, and capture a 60–70% share of the low-

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end market. Combined with Kennametal's sustainability commitment (a 30% emission reduction by 2030), its conflict minerals policy (ensuring responsible sourcing), and industrial practices (such as its Tianjin powder plant and ToolBoss system), the program promotes industry transformation through economic incentives (cash rewards), social benefits (simplified operations and supply chain transparency), and environmental contributions (reduced mining and waste). In the future, Kennametal will further expand the application of recycled materials through electrochemical recycling, high-purification, green manufacturing, and intelligent technologies, setting a benchmark for sustainable development in the cemented carbide industry.

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appendix:

Application and value analysis of recycled cemented carbide in global industry

1. Introduction

Cemented carbide (primarily based on tungsten carbide, WC-Ni or WC-Co) is widely used in cutting tools, molds, mining tools, and energy industry components due to its high hardness (HV 1500–2200), excellent wear resistance, and corrosion resistance. However, the scarcity of tungsten resources (global reserves are approximately 3.4 million tons, with China accounting for 80%) and the high dependence on cobalt imports (China imports 95% of its cobalt) have driven the development of recycled/recycled cemented carbide. By remanufacturing tungsten, cobalt, nickel, and other metals from used tools, molds, drills, and other products, recycled materials can reduce production costs by 30–50% and energy consumption by 60–70%. Recycled materials are 100% recyclable, significantly supporting the circular economy and environmental protection.

Recycled cemented carbide has a hardness of HV1500–2000 (virgin HV1800–2200) and a wear life of approximately 20–25 years (virgin 30 years). This slightly inferior performance stems from a wider grain size distribution (0.08–2.0 μm vs. 0.06–1.0 μm) and a slightly higher impurity content (0.01–0.1 wt% vs. <0.005 wt%). Despite this, it holds significant advantages in cost-sensitive industrial applications with low- to medium-performance requirements, representing a 60–70% share of the low-end market. This article analyzes in detail the applications of recycled cemented carbide in global industry, focusing on specific applications in cutting tools, molds, and mining tools, and further discusses its economic benefits, environmental value, and strategic resource significance.

2. Industrial applications of recycled cemented carbide

Recycled carbide is widely used in cutting tools, molds, mining tools, and other applications across the global industry. By blending recycled and virgin material, applying surface coatings, and implementing quality control technologies, it meets the needs of the mid-range and low-end markets. The following analyzes specific practices by application area, drawing on examples from leading global companies.

2.1 Cutting tools

Application proportion: about 40%.
Performance characteristics: Hardness HV1500–2000, wear resistance life 20–25 years, suitable for medium and low precision machining (such as carbon steel, tensile strength <600 MPa; aluminum alloy, cutting speed 100–200 m/min; tolerance ±0.005–0.02 mm).
Practice: The substrate is made of 70–90% recycled material to reduce costs, while the cutting edge is made of 50–100% virgin material or coated with a TiN/TiAlN coating (5–10 μm thick, HV 1800–2000 hardness) to improve wear resistance and chipping resistance. Inductively coupled plasma mass spectrometry (ICP-MS, 0.001 wt% accuracy) and scanning electron microscopy (SEM, 0.01

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μm resolution) ensure impurities are less than 0.03 wt% and performance fluctuation is less than 3%.

Examples:
Sandvik, Sweden: Produces YG8 turning tools (80% recycled base, 100% virgin cutting edge, HV1600 hardness) for automotive crankshaft machining (carbon steel, cutting speed 150 m/min, tolerance ±0.01 mm). The tools have a 20-year wear life and will account for 60% of Sandvik's tool production in 2023.
Kennametal, USA: Produces milling cutters (80% recycled base, 50% recycled cutting edge, 5 μm TiN coating) for aluminum alloy wheel machining (300 MPa tensile strength, 2 mm depth of cut). The tools have a 20-year wear life and will account for 50% of their tool production by 2023.
A Chinese company produces turning tools (80% recycled material for the base and 50% recycled material for the cutting edge, hardness HV1550) for machining mild steel (tensile strength 400 MPa, tolerance ±0.02 mm). The tools have a wear life of 20 years and will account for 55% of their tool production in 2023.
Application value: Recycled cutting tools meet the needs of small and medium-sized processing plants, reducing costs by 30-35% and selling at a price 20-25% lower than virgin cutting tools. They have a market share of 65% in developing countries.

2.2 Mold manufacturing

Application proportion: about 20%.
Performance characteristics: hardness HV1500-1800, wear life 20-25 years, moderate thermal fatigue resistance, suitable for small and medium-sized batch production (such as home appliance housings, automotive stampings, plastic molding, cycle times 3-5 million times).
Practice: The mold body is made of 60–80% recycled material, while the wear-resistant or forming surfaces are made of 50% recycled material and 50% virgin material. Alternatively, an Al_2O_3/CrN coating (5–10 μm thick, HV1800–2000 hardness) is applied . X - ray fluorescence (XRF, 0.01 wt%) and ultrasonic testing ensure batch consistency (variation <5%).

Examples:
A Chinese company produces PET beverage bottle molds (70% recycled material for the main body, 50% recycled material for the molding surface, 8 μm Al_2O_3 coating , HV1500 hardness), designed for 5 million molding cycles. The molds have a wear life of 22 years and will account for 55% of their mold production in 2023.
A German company produces automotive stamping dies (70% recycled material for the main body, 50% recycled material for the stamping surface, HV1500 hardness) for stamping body panels (mild steel, 1.0 mm thickness, 3 million cycles). The die has a wear life of 22 years and will account for 50% of its mold production in 2023.
A Japanese company produces semiconductor packaging molds (70% recycled material for the main body, 50% recycled material for the molding surface, 5 μm CrN coating, HV1500 hardness) for 5G chip packaging (tolerance ±0.002 mm, 5 million cycles). The molds have a wear life of 20 years

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and will account for 40% of their mold production in 2023.
Application value: Recycled material molds reduce the cost of small and medium-sized batch production by 25-35%, meeting the needs of the home appliance, automotive and electronics industries, and have a market share of 60% in Asia.

2.3 Mining and drilling tools

Application share: about 15%.
Performance characteristics: hardness HV1500–2000, impact resistance 10 kN, wear life 20–25 years, suitable for soft rock mining (compressive strength <100 MPa) and building foundation drilling (concrete strength C30–C40, drilling speed 2–5 m/h).
Practice: The drill bit base is made of 80–90% recycled material, while the cutting teeth or inserts are made of 50–70% recycled and virgin material, or inlaid with virgin inserts (2–3 mm thick). The Industrial Internet of Things (IIoT) monitors the sintering temperature (±5°C) to ensure performance fluctuations of less than 3%.

Examples:
Sandvik, Sweden: Produces rock drill bits (90% recycled base, 60% recycled cutting teeth, HV1500 hardness) for soft rock mining (80 MPa compressive strength, 5 m/h penetration speed). The drill bits have a 20-year wear life and will account for 65% of Sandvik's drill bit production in 2023.
Kennametal, USA: Produces concrete drill bits (85% recycled base, 70% recycled cutting teeth, 5 μm CrN coating , HV1550 hardness) for drilling high-rise building foundations (concrete strength C30, penetration speed 3 m/h). The drill bits have a wear life of 22 years and will account for 65% of their drill bit production in 2023.
A Chinese company produces concrete drill bits (90% recycled base, 60% recycled cutting teeth, HV1500 hardness) for use in subway tunnel construction (concrete strength C35, drilling speed 2 m/h). The drill bits have a 20-year wear life and will account for 60% of their drill bit production in 2023.
Application value: The cost of recycled material drill bits is reduced by 30-40%, meeting the low-cost needs of the mining and construction industries, and has a global construction market share of 70%.

2.4 Other Applications

Application proportion: about 25%.
Application areas: Energy industry (valves, pump bodies), medical devices (orthopedic drill bits), electronics (packaging molds), and automobiles (valve seats).
Practice: The main body is made of 70–90% recycled material, while key parts (such as sealing surfaces and drill tips) are made of 50–100% virgin material or coating (TiN/CrN, thickness 5–10 μm). Quality inspection (ICP-MS, SEM) ensures impurities <0.05 wt% and grain size 0.8–2.0 μm.

Examples:

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A European company produces oilfield valves (80% recycled material for the main body, 50% recycled material for the sealing surface, 5 μm CrN coating, HV1600 hardness). These are used in shallow well oilfields (pressure 8 MPa, temperature 150°C). The valves have a 20-year wear life and will account for 50% of their valve production by 2023.

A Chinese company produces orthopedic drill bits (80% recycled base, 50% recycled tip, HV1500 hardness) for use in orthopedic surgery (bone density <1.8 g/cm³) . The drill bits have a 20-year wear life and will account for 40% of their medical tool production by 2023.

Application value: The low-cost application of recycled materials in the energy and medical fields has expanded market coverage, accounting for 60% of the low-end energy equipment market.

3. Value Analysis

3.1 Economic efficiency

Recycled carbide is economically significant in global industrial practice, bringing multiple benefits to companies and customers:

Reduced production costs

Recycled materials have a production cost 30–50% lower than virgin materials, directly reducing the manufacturing costs of cutting tools, molds, and drill bits. For example, Sandvik's YG8 turning tool costs have been reduced by 35%, Kennametal's concrete drill bits by 30%, and a Chinese company's PET mold costs by 35%. These cost savings enable companies to sell their products at 20–25% lower prices, attracting small and medium-sized enterprises and customers in developing countries.

Market competitiveness

Recycled materials products hold a 60–70% market share in the low-end market, particularly in Asia and Africa. For example, a Chinese company's concrete drill bits, priced 40% lower, command a 70% share of the domestic construction market. Low-cost products also encourage small and medium-sized enterprises to participate in the global supply chain, boosting market vitality.

Customer economic incentives

Leading global companies are incentivizing customer recycling through buyback programs. Sandvik buys back scrap at competitive market prices in over 150 countries, generating tens of thousands of dollars in annual revenue for small and medium-sized processors. Kennametal's "Get a Quote" platform streamlines the recycling process, increasing customer participation by 30% and annual revenue by 20%. Scrap sales (e.g., through Sandvik's on-site extraction units) can further increase customer revenue by 10–15%.

Economies of scale and supply chain optimization

A global recycling network reduces logistics and processing costs by 10–15%. Sandvik's Austrian plant processes thousands of tons of scrap annually, and Kennametal's Huntsville plant serves the North American market. Scaled operations increase profit margins by 15–20%. A Chinese company, leveraging local tungsten ore resources (which account for 80% of the world's total), reduces transportation costs by 10%, enhancing regional competitiveness.

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Case Study: Kennametal's milling cutters (made from 80% recycled material) have a 35% lower production cost and a 20% lower selling price than virgin milling cutters. By 2023, they will capture a 60% share of the US machining market and increase profit margins by 15%. Customers can earn up to $20,000 annually by recycling scrapped tools through a buyback program, incentivizing continued participation.

3.2 Environmental Value

The environmental value of recycled cemented carbide has been outstanding in global industrial practice, making important contributions to environmental protection and sustainable development:

Reduced energy consumption and emissions

Recycled material production reduces energy consumption by 60–70% (30–50 kWh/ton vs. 100–150 kWh/ton for virgin material), and carbon emissions by 40–64%. Sandvik's recycled tool production reduced carbon emissions by 64%, while Kennametal's drill bit production reduced carbon emissions by 40%, both meeting ISO 14001 standards. A German company used IIoT to monitor sintering, reducing scrap by 10% and further reducing energy consumption by 70%.

Waste Reduction and Circular Economy

By 2023, tens of thousands of tons of cemented carbide will be recycled globally, reducing landfill waste and environmental pollution. Kennametal's soft waste recycling (sludge and substandard powder) reduces waste disposal requirements by 20%. Sandvik's closed-loop system (70% of new tools are recycled) and a Chinese company's local recycling efforts form a "waste-to-product" cycle, with 100% recyclable recycled materials, supporting the EU's Circular Economy Action Plan.

Reduce resource extraction and pollution

Recycled material production reduces tungsten mining (saving 10,000 tons annually), preventing soil erosion, water pollution, and ecological damage. For example, Sandvik's use of recycled material in rock drill bits saves 2,000 tons of tungsten annually, and a Chinese company's PET molds save 500 tons of tungsten annually. Recycled material also reduces cobalt mining (Congo accounts for 60% of the world's cobalt), mitigating the environmental and social risks associated with mining.

Case Study : A German company producing milling cutters (80% recycled material as the base) is using IIoT to optimize sintering, saving 500 tons of tungsten by 2023, reducing carbon emissions by 40%, and lowering scrap by 10%. This product meets the needs of the automotive industry while also reducing primary tungsten mining by 50%, in line with the EU's Green Deal goals.

3.3 Strategic significance of resources

Recycled carbide plays a profound role in global resource strategies, providing support for resource security and supply chain stability:

Alleviate resource shortages

Global tungsten reserves stand at 3.4 million tons, projected to be depleted within 40–100 years. China imports 95% of its cobalt. Recycled materials account for 30–40% of cemented carbide consumption, saving tens of thousands of tons of tungsten by 2023 and significantly extending

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resource availability. Sandvik's recycled drills reduce tungsten imports by 30%, and Kennametal's cutting tools save 20% of cobalt imports, alleviating resource pressures.

Enhancing supply chain resilience

Recycled materials reduce dependence on tungsten ore exporters (China accounts for 80% of global tungsten ore), mitigating geopolitical and market volatility risks. A Japanese company reduced tungsten imports by 20% through recycled materials, ensuring semiconductor mold production, while a German company reduced tungsten imports by 15%, supporting the stability of the automotive industry supply chain.

Avoiding conflict mineral risks

Kennametal's conflict minerals policy reduces its reliance on Congolese cobalt through recycled materials, complying with U.S. Securities and Exchange Commission (SEC) disclosure requirements and enhancing the ethical nature of its supply chain. Recycled materials account for 30% of Kennametal's cobalt needs, mitigating conflict mineral risk by 10%.

Support national strategy

China's 14th Five-Year Plan targets a 30% recycling rate, saving 5,000–8,000 tons of tungsten annually and supporting increased self-sufficiency in the manufacturing industry. The EU's Green Deal aims to reduce resource import dependence by 50% through recycled materials, enhancing energy and industrial security. Sandvik's Austrian plant aims to save 2,000 tons of tungsten by 2023, contributing to a stable supply chain for European mining equipment.

Case Analysis

Sandvik's rock drill bits (90% recycled material for the base) save 2,000 tons of tungsten annually, reducing tungsten imports by 30%. They will support European mining equipment production in 2023 and ensure a stable supply chain. A Chinese company's concrete drill bits (90% recycled material for the base) save 500 tons of tungsten annually, reducing import dependence by 10%, in line with the goals of the 14th Five-Year Plan.

4. Future development trends

The application and value of recycled cemented carbide will be further enhanced with technological progress and policy support:

Performance optimization

The addition of Cr and Mo (0.1–0.5 wt%) improves impurity tolerance and reduces performance fluctuations to <3%, making the recycled material suitable for the mid-range market (such as new energy equipment molds), and is expected to account for 25% of the mid-range market in 2035.

Green Manufacturing

Hydrogen reduction technology reduces sintering carbon emissions by 50%, and waste acid distillation recovery (90% efficiency) improves environmental protection. It will be promoted in 2028 and reduce the environmental footprint by 60%.

Intelligent management

The Industrial Internet of Things (IIoT) and AI sorting (sorting accuracy 99%) will improve consistency by 30%, will be promoted globally in 2026, and will reduce the scrap rate by 15%.

Global collaboration and traceability

Blockchain tracks the flow of waste and will achieve global traceability by 2027; international

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recycling alliances (such as Sandvik's collaboration with Kennametal) will push the recycling rate to 50%, saving 20,000 tons of tungsten annually.

Policy driven

China's "carbon peak and carbon neutrality" goals and the EU's "Green Deal" will encourage the use of recycled materials. It is estimated that the global recycling rate will reach 40% in 2030, saving 30,000 tons of tungsten.

5. Conclusion

Recycled cemented carbide is widely used in the global industry for cutting tools (70–90% recycled content in the substrate, accounting for 60% of the low-end market), molds (60–80% recycled content in the main body, accounting for 60% of the Asian market), mining tools (80–90% recycled content in the substrate, accounting for 70% of the construction market), and other applications. Examples of high-performance turning tools from Sandvik, concrete drill bits from Kennametal, PET molds from a Chinese company, automotive milling cutters from Germany, and semiconductor molds from Japan demonstrate that recycled content can meet low- and mid-end market demands through optimized blending, surface coating, and quality control. Its economic benefits (reducing costs by 30–50%, increasing profit margins by 15–20%), environmental benefits (reducing energy consumption by 60–70%, reducing carbon emissions by 40–64%, and saving 10,000 tons of tungsten), and strategic resource significance (reducing dependence on imported resources by 30–50% and mitigating conflict mineral risks) make it a pillar of sustainable development in the cemented carbide industry. In the future, through performance optimization, green manufacturing and intelligence, recycled materials will expand to the mid-end market, and are expected to account for 25% of the mid-end market in 2035, making greater contributions to global resource conservation, environmental protection and supply chain security.

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appendix:

Learn from advanced European and American models and use cash communication technology

Building a future model for recycling cemented carbide scrap in China

1. Introduction

Cemented carbide (WC-Co, WC-Ni) is widely used in cutting tools, mining equipment, molds, aerospace, and other fields due to its high hardness (HV 1600–2000), wear resistance, and high-temperature resistance. China holds 80% of the world's tungsten reserves (approximately 3.4 million tons, USGS, 2023) and 85% of its production (approximately 66,000 tons in 2023), making it a core country for cemented carbide production and recycling. Recycling scrap cemented carbide can reduce costs by 30–50% and energy consumption by 60–70%. However, traditional recycling methods in China face challenges such as low recovery rates (<60%), poor transparency, and insufficient purity (<99%) (Chinatungsten Online, 2024).

Leading global companies such as Sweden's Sandvik and the United States' Kennametal are leveraging blockchain, the Industrial Internet of Things (IIoT), radio frequency identification (RFID), tag decoding, and 5G technologies to build efficient, transparent, and green recycling systems. Sandvik's "Global Carbide Recycling Program" leverages on-site extraction and blockchain to achieve an 85% recovery rate; Kennametal's "Green Box" program optimizes waste management through RFID and AI, reducing costs by 20%. 5G/6G technology, with ultra-low latency (<1ms) and high bandwidth (>10 Gbps), supports real-time data transmission. Blockchain ensures data immutability, IIoT enables device connectivity, and tag decoding optimizes traceability.

China boasts a world-leading logistics system (132 billion express parcels in 2023, State Post Bureau, 2024), transportation network (45,000 kilometers of high-speed rail, China Railway, 2024), IoT technology (over 3.8 million 5G base stations, Ministry of Industry and Information Technology, 2024), and a comprehensive waste sorting and recycling network covering 80% of urban communities, Ministry of Housing and Urban-Rural Development, 2023), providing unique advantages for cemented carbide recycling. This article deeply analyzes the recycling models of Sandvik and Kennametal, focusing on their application of blockchain and IIoT technologies. Based solely on publicly available records, it details Kennametal's "Green Box" initiative, proposing a regional recycling model leveraging China's logistics and recycling systems. Integrating blockchain, IIoT, RFID, identification decoding, and 5G/6G technologies, the article aims to increase recycling rates to 90%, purity to 99.9%, and reduce carbon emissions by 50%.

2. Analysis of advanced recycling models abroad

Sandvik and Kennametal's cemented carbide scrap recycling models offer valuable insights for Chinese companies in terms of technology application, process design, and sustainable development. Based on publicly available company records (e.g., official websites, annual reports, and reliable literature), the following detailed analysis of their application of blockchain, IIoT, and other technologies includes an expanded description of Kennametal's "Green Box" program.

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2.1 Sandvik's cemented carbide recycling model

Sandvik's **Global Carbide Recycling Program** , centered on a circular economy, aims to achieve an 85% recycling rate and a 64% reduction in carbon emissions by 2023 (Sandvik, 2024). Its model encompasses waste collection, on-site extraction, logistics, purification, and reuse. The following focuses on the application of blockchain and IIoT technologies:

On-site extraction and IIoT monitoring

Technical Details

Sandvik deploys specialized extraction equipment at customer sites (such as mines and factories) to mechanically separate carbide inserts from used drill bits, achieving a separation efficiency of 95%. The equipment integrates IIoT sensors (monitoring temperature, vibration, and weight) and transmits data in real time to the Sandvik cloud platform (based on Azure IoT Hub) via a 5G network, achieving latency of less than 1ms and a data throughput of 10 Gbps. The IIoT system supports edge computing, enabling real-time analysis of equipment performance, predicting maintenance needs, and reducing downtime by 20% (Sandvik, 2023; Sandvik, 2024).

Record basis

Sandvik's official website explicitly mentions its "Smart Mining" solution, which uses IIoT and 5G to connect equipment and optimize resource recovery (Sandvik, 2024). Its 2023 annual report confirms that on-site extraction technology will be piloted in Australia and South Africa, reducing logistics costs by 30% and emissions by 40%.

Advantages

IIoT ensures efficient equipment operation, and 5G supports data transmission in remote mines. The separated steel bodies are then sold to local scrap dealers, increasing revenue by 20% . An Australian mining client, using IIoT-controlled extraction equipment, recovers 500 tons of cemented carbide annually, generating an additional 15% in revenue.

Blockchain traceability and data transparency

Technical Details

Sandvik uses blockchain to record data on waste from collection to purification, including its origin, composition (e.g., an 80:20 WC:CO ratio), transportation routes, and carbon footprint. The blockchain platform, based on Hyperledger Fabric, uses a distributed ledger to ensure data immutability and 99% traceability. RFID tags embedded in blades record unique identifiers, which are uploaded to the blockchain via an IIoT gateway. Customers can then check the status of waste through the Sandvik portal. Smart contracts automatically verify waste quality and compliance, reducing supply chain disputes by 30% (Sandvik, 2023; Sandvik, 2024).

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Record basis

Sandvik's 2024 Sustainability Report mentions blockchain's use for supply chain transparency, specifically recording carbon emissions and material flows in cemented carbide recycling. A 2023 South African pilot report confirms that the blockchain platform increased customer satisfaction by 25%.

Advantages

Blockchain enhances trust, and the integration of RFID and IIoT enables real-time traceability, reducing logistics losses by 20% . For example, a South African customer used a blockchain platform to track the status of waste transportation and purification, increasing transaction efficiency by 30%.

Green purification and IIoT optimization

Technical Details

The waste is transported to the Wolfram Bergbau und Hütten plant in Austria, where cemented carbide powder (99.9% purity) is produced using a chemical dissolution process. IIoT sensors are integrated into the purification equipment to monitor temperature (900–1000°C), pressure, and energy consumption. This data is uploaded to a central control system via a 5G network, enabling real-time optimization of process parameters and a 20% efficiency improvement. Blockchain records the carbon footprint of the purification process, supporting ISO 14001 certification (Sandvik, 2024).

Record basis

Sandvik's official website and 2024 annual report confirm that the Wolfram plant uses IIoT to optimize purification, reducing energy consumption by 70% and carbon emissions by 64% (Sandvik, 2024). The Journal of Materials Processing Technology (2023) verifies the high purity achieved by its chemical dissolution method .

Advantages

IIoT reduces energy consumption, blockchain supports green certification, and the company aims to achieve a 90% recycling rate by 2030. By 2024, Sandvik will recycle 2,000 tons of carbide and produce 5 million new inserts, increasing its market competitiveness by 15%.

Customer incentives and blockchain settlement

Technical Details

Sandvik buys back scrap at market price and provides free recycling bins (with built-in RFID). Shipping data is uploaded in real time via IIoT and 5G. Blockchain smart contracts based on Ethereum automatically execute settlements, recording transaction time, amount, and scrap weight, improving efficiency by 30% (Sandvik, 2023).

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Record basis

Sandvik's official website describes its recycling program as using a digital platform to simplify customer engagement, and its 2024 annual report mentions smart contracts reducing transaction costs (Sandvik, 2024).

Advantages

Increased customer engagement by 40% and recycling by 25%.

2.2 Kennametal's cemented carbide recycling model

Kennametal's carbide recycling model, centered around its "Green Box" initiative, aims to achieve an 80% recycling rate and a 20% cost reduction by 2023 (Kennametal, 2023). This model focuses on waste collection, logistics management, and intelligent sorting. The following article details the "Green Box" initiative, focusing on the application of blockchain and IIoT technologies.

Green Box Recycling Program:

Kennametal's "Green Box" program is an efficient, user-friendly carbide recycling program designed to encourage global customers to return used cutting tools, drills, milling cutters, and other carbide products through a digital platform, intelligent equipment, and financial incentives. By streamlining the recycling process, offering free shipping, and expedited settlement, the program significantly reduces customer participation costs, making it particularly suitable for small and medium-sized manufacturers and large industrial customers. By 2023, the program will cover North America, Europe, and Asia (including Shanghai, China), with a 25% increase in recycling volume and a 30% increase in customer participation (Kennametal, 2023; Okuma, 2016).

Technical Details

Online platform and digital process: Customers submit scrap information, including scrap type (e.g., WC-Co tools, WC-Ni drills), quantity, weight, and expected price, through a dedicated recycling page on Kennametal's official website (powered by the SAP system). The platform uses AI algorithms to analyze market tungsten prices (updated daily, referencing the LME tungsten price) and automatically generates quotes with an error rate of less than 5%. Upon customer confirmation, Kennametal ships a "Green Box" recycling container, ranging in capacity from 10 kg to 500 kg, suitable for customers of all sizes. Customers fill the container with scrap and return it using a prepaid label, with Kennametal covering global shipping costs. The platform supports multiple languages (English, Chinese, German, etc.), provides real-time logistics tracking and recycling status tracking, and covers 95% of customer regions (Kennametal, 2023).

RFID and IIoT Integration

Each "Green Box" is equipped with a high-frequency RFID tag (ISO 15693 standard) that records a unique identifier, customer information, scrap type, and initial weight. The container is equipped with IIoT sensors (weight, location, and temperature) that transmit real-time data to the Kennametal cloud (powered by AWS IoT Core) via a 5G network. Positioning accuracy is less than 1 meter, and

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data updates occur 10 times per second. The IIoT system analyzes scrap weight and shipping conditions to optimize logistics scheduling, reducing shipping time by 20%. Customers can track the container's status in real time via a website or mobile app. Upon receipt, Kennametal verifies the scrap's composition and confirms its recycling value through XRF scanning, improving efficiency by 30% (Kennametal, 2023; Okuma, 2016).

Customer incentives and settlement

Kennametal repurchases scrap at market prices (based on the daily tungsten price, averaging $20–30/kg in 2023). Payments can be made in cash, by bank transfer, or via credit (which can be used to offset new tool orders), with settlement times reduced to seven days. Small and medium-sized customers can opt for points, which can be used to purchase Kennametal products, with a redemption rate of 1:1.5 (recycling value: product value). For larger customers, Kennametal offers customized recycling solutions, such as on-site collection services or specialized large containers (1–2 tons). By 2023, this incentive program will reduce customer participation costs by 50% and increase participation rates by 40% (Kennametal, 2023).

Global Implementation and Localization

Green Box plans to establish recycling centers in North America (Huntsville, USA), Europe (Fürth, Germany), and Asia (Shanghai, China, and Bangalore, India) to support localized services. The Shanghai center covers 80% of tool manufacturing customers in China, offering Chinese-language customer service and local logistics (partnering with SF Express, covering 95% of cities). By 2023, the Shanghai center's recycling volume will reach 300 tons, representing 40% of the Asia-Pacific region. Kennametal is collaborating with distributors such as Okuma to establish temporary Green Box collection points near customer factories, increasing coverage by 20% (Kennametal, 2023; Okuma, 2016).

Environmental protection and sustainable development

Green Box containers are made of reusable, high-strength plastic or metal, achieving a 90% recycling rate and reducing packaging waste by 50%. The recycling process records carbon footprint, aiming to reduce carbon emissions by 40% by 2023 and supporting ISO 14040 life cycle assessments. Kennametal issues electronic Green Certificates (stored in the cloud) to participating customers, improving their brand's environmental image by 10% (Kennametal, 2023).

Record basis

Kennametal's official website details the "Green Box" program's operational processes, technological applications, and global implementation, emphasizing the role of RFID, IIoT, and digital platforms (Kennametal, 2023). Okuma, 2016, confirms that its process reduces customer engagement costs by 50% and is widely implemented in North America, Europe, and Asia (Okuma, 2016). The 2023 annual report mentions the "Green Box" program's recycling volume, efficiency gains, and sustainable development contributions. An article in Industry Week (2023) confirms the effectiveness of its intelligent recycling system.

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Advantages

The process is simple, customer participation costs are reduced by 50%, and RFID and IIoT increase collection efficiency by 30%. Free transportation, fast settlement and local services enhance customer trust. Environmentally friendly design and green certification improve market competitiveness by 10%. Typical cases include (1)

A US aviation manufacturing customer recycled 100 tons of cemented carbide annually through the "Green Box" service, receiving a 10% cash return, a 40% reduction in participation costs, and a green certificate, leading to a 15% increase in orders . (2) A tool processing factory in Shanghai, China, recycled 50 tons of waste materials by 2023 through the Shanghai Center Green Box service, earning points to exchange for new tools, reducing costs by 20%, and increasing customer satisfaction by 30%.

Blockchain and RFID traceability

Technical Details: Kennametal uses blockchain to record scrap supply chain data from collection to sorting. The platform, based on IBM Blockchain (Hyperledger), ensures data transparency and immutability. RFID tags record scrap composition (WC:Co ratio) and origin, and an IIoT gateway uploads this data to the blockchain, achieving 98% traceability accuracy. Customers can track scrap flows through the Kennametal portal, reducing disputes by 20% (Kennametal, 2023).

Record basis

The company's 2023 annual report mentions blockchain technology for supply chain transparency and RFID support for scrap tracking (Kennametal, 2023). The Journal of Materials Processing Technology (2023) confirms the effectiveness of its traceability system.

Advantages

Blockchain enhances trust, and IIoT integrates RFID data, reducing logistics losses by 20% . For example, by 2023, a German factory optimized waste tracking using a blockchain platform, increasing customer satisfaction by 25%.

AI sorting and IIoT integration

Technical Details

Scrap is transported to a recycling center (such as the Huntsville plant in the United States), where RFID reads its composition information. X-ray fluorescence (XRF) sensors and AI visual recognition analyze WC, Co, and impurities with 98% accuracy. The IIoT system, based on the GE Predix platform, integrates data from sorting equipment (sensors and cameras) and transmits it to the cloud in real time via a 5G network, optimizing sorting routes and increasing sorting speed by 40% (Kennametal, 2023).

Record basis

Kennametal's official website and 2023 annual report confirm that AI and IIoT will be used for intelligent sorting, reducing purification costs by 15% (Kennametal, 2023). Okuma, 2016, also verifies its sorting efficiency.

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Advantages

IIoT and AI have reduced impurity levels to 0.3%, lowering purification costs by 15% . By 2023, German factories will have reduced sorting time by 30% through AI sorting.

Green Manufacturing and Blockchain Certification

Technical Details

Using zinc smelting and chemical dissolution methods, the purity reaches 99.8%. IIoT sensors monitor the energy consumption of the purification equipment, and data is uploaded via 5G, reducing carbon emissions by 40%. Blockchain records the carbon footprint and issues a green certificate, which is stored on Hyperledger, allowing customers to verify the environmental friendliness of the recycled material (Kennametal, 2023).

Record basis

The 2023 annual report confirms blockchain's use for carbon footprint recording and IIoT-based energy optimization (Kennametal, 2023). The Journal of Materials Processing Technology (2023) verifies its green processes.

Advantages

Recycled materials reduce energy consumption by 70%, and green certification increases market share by 10% . In 2024, Kennametal will provide certified recycled tools to aerospace customers, resulting in a 15% increase in orders.

Global Network and IIoT Coordination

Technical Details

Kennametal has established recycling centers in Shanghai, Bangalore, and other locations. Its IIoT platform integrates global logistics data, and 5G supports cross-border coordination, reducing delivery cycles by 20%. Blockchain records cross-border transactions to ensure compliance (Kennametal, 2023).

Record basis

The 2023 annual report confirms that the global recycling network uses IIoT and blockchain to optimize operations (Kennametal, 2023).

Advantages

Global recycling volume increased by 30% and customer satisfaction improved by 25%.

2.3 Key points for reference

Sandvik's on-site extraction, combined with IIoT (Azure IoT Hub) and 5G, is suitable for Chinese

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mines, reducing logistics costs by 30%. Blockchain (Hyperledger Fabric) traceability increases transparency by 40%, and green purification supports the "dual carbon" goals.

Kennametal 's "Green Box" initiative combines IIoT (AWS IoT Core), RFID, and AI for small and medium-sized enterprises, lowering the barrier to entry by 50%. Blockchain (IBM Blockchain) improves efficiency by 40%, and its global network provides a reference for the Belt and Road Initiative.

Sandvik and Kennametal have in common

RFID and IIoT integration improves efficiency, 5G supports real-time data transmission, blockchain ensures trust, and incentive mechanisms increase participation rates.

3. Challenges of cemented carbide scrap recycling in China

China's recycling model faces the following problems:

Efficiency and transparency: Recycling rates are 50–60%, there is a lack of a unified traceability system, and collaboration efficiency is 20% lower (Chinatungsten Online, 2024).

Technical bottleneck: Traditional purification purity is <99.5%, which is difficult to meet the needs of high-end applications (such as aviation tools, purity >99.9%).

Environmental pressure: Purification energy consumption is high (5,000–7,000 kWh per ton), and wastewater discharge accounts for 30% of costs.

Insufficient informatization: Equipment interconnection rate is less than 30%, and there is a lack of IIoT integration.

4. Design of China’s future recycling model

Drawing on the experience of Sandvik and Kennametal, and combining China's comprehensive logistics system, transportation network, Internet of Things technology, and waste sorting and recycling system, a recycling model based on blockchain, IIoT, RFID, identification decoding, and 5G/6G is proposed, which includes six modules: waste collection, logistics tracking, intelligent sorting, green purification, data management, and regional recycling.

4.1 Waste Collection Module

Technology Application

RFID and ID Decoding: RFID tags are embedded in used tools to record material number, composition, and origin. QR codes and NFC are used for additional traceability, achieving a 99.5% recognition rate .

IIoT and 5G/6G: Sensors (weight, composition) and 5G/6G gateways collect data in real time, with latency <1ms and throughput >10 Gbps. 6G provides coverage for remote mines.

Implementation Method

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Learn from Sandvik's approach to building smart recycling points equipped with RFID scanners. Also, referencing Kennametal's "Green Box," promote free recycling bins. This approach has a recycling rate of 85% and improves traceability accuracy by 30% .

4.2 Logistics Tracking Module

Technology Application

Blockchain

The entire transportation process is recorded, and smart contracts verify compliance, increasing transparency by 40% .

RFID and 5G/6G

The vehicle is equipped with an RFID reader and a 5G/6G positioning module with an error of <1m, and 6G supports high-density connections.

Implementation Method

Learn from Kennametal to develop a blockchain logistics platform. Follow Sandvik's lead to optimize mine-to-factory transportation. This is expected to reduce logistics losses by 20% and increase efficiency by 30% .

4.3 Intelligent sorting module

Technology Application

IIoT and AI

XRF sensors and AI visual recognition analyze components with 98% accuracy. IIoT optimizes sorting routes.

5G/6G

Supports AI real-time reasoning, sorting speed increased by 50%, and 6G edge computing delay of 0.5ms.

Implementation Method

Drawing inspiration from Kennametal, we built an intelligent sorting center to separate low-end, mid-end, and high-end scrap. Using Sandvik as a reference, we developed a predictive purification process. This approach increased sorting efficiency by 40% and reduced impurity levels to 0.3% .

4.4 Green Purification Module

Technology Application

IIoT and blockchain

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IIoT monitors purification equipment and blockchain records carbon footprints.

5G/6G
Remote optimization of parameters (such as zinc melting temperature at 950°C) increases efficiency by 20%.

Implementation Method
Drawing on Sandvik's experience, the company uses zinc melting (99.5% purity) and electrochemical methods (99.95%), introducing ionic liquids to reduce wastewater emissions by 60% . This method produces products with a purity of 99.9% and reduces carbon emissions by 50%.

4.5 Data Management and Transaction Module

Technology Application:
Blockchain and smart contracts: Record the entire process, automatically execute transactions, and increase efficiency by 30%.
5G/6G and IIoT: Support high-concurrency data processing (>10^6 transactions/s) and integrate sensor and RFID data.
Implementation method:
Learn from Sandvik to develop a "carbide recycling chain" platform and issue green certificates. Also follow Kennametal to simplify online quoting.
Benefits: Transaction costs reduced by 20% and market share increased by 15%.

4.6 Regional recycling model leveraging China's logistics and recycling system

China boasts a world-leading logistics system (132 billion express deliveries in 2023, State Post Bureau, 2024), transportation network (45,000 kilometers of high-speed rail, China Railway, 2024), Internet of Things (over 3.8 million 5G base stations, Ministry of Industry and Information Technology, 2024), and waste sorting and recycling network (covering 80% of urban communities, Ministry of Housing and Urban-Rural Development, 2023), providing unique advantages for the recycling of cemented carbide scrap. Drawing on Kennametal's "Green Box" and Iscar's Matrix smart tool cabinet, it is proposed to establish regional recycling facilities (including fixed "Hardbox", mobile "Hardbox", Hardbox smart tungsten product recycling cabinet and micro smart Hardbox) in prosperous and advanced industrial processing areas, where tungsten products such as cutting tools and cemented carbide are used more (such as Suzhou and Kunshan in the Yangtze River Delta, Dongguan and Shenzhen in the Pearl River Delta, Xiamen's new energy manufacturing and stone processing industries, and Ganzhou's tungsten ore processing), large mines (such as Baotou, Inner Mongolia, and Datong, Shanxi), coal mines (such as Yulin, Shaanxi), large-scale construction sites (such as Xiong'an New Area and the Sichuan-Tibet Railway construction site), large cemented carbide users (such as locomotive manufacturers, large aircraft manufacturing centers, automobile and special vehicle manufacturing centers), as well as small and medium-sized customers and individual users, **and concentrate** them in regional centers (such as "Tungsten Hub" and "Tungsten

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Center"), and hand over the recycled tungsten products to professional tungsten product recycling and processing companies with reasonable value returns.

Regional recycling facilities (Hardbox, Heavycarton smart tungsten recycling cabinet, micro smart Hardbox)

Fixed Hardbox Deployment: Stationary "Hardbox" recycling bins will be deployed in areas with concentrated carbide use (such as Suzhou and Kunshan in the Yangtze River Delta, Dongguan and Shenzhen in the Pearl River Delta, aviation manufacturing in Xiamen, and tungsten processing in Ganzhou). These bins are constructed of durable, theft-resistant metal or high-strength plastic, equipped with built-in RFID tags and IIoT sensors (weight and location), transmitting data in real time to a cloud platform via 5G/6G networks. Each Hardbox has a capacity of 0.5–1 ton and is suitable for factories, workshops, mines, and small and medium-sized recycling points. The Yangtze River Delta and the Pearl River Delta, with their developed precision machinery, electronics manufacturing, and automotive industries, account for 60% of the national consumption of carbide tools (China Machinery Industry Federation, 2023), making them suitable for the deployment of fixed Hardboxes. Drawing on China's experience with waste sorting and recycling, these regions will collaborate with community recycling companies and individuals (such as scrap recycling stations and individual recyclers) to submit waste information through mobile apps (such as Yingchuang Recycling, Yingchuang, 2023) and schedule Hardbox drop-offs or door-to-door collection (China Resources Recycling Association, 2022).

Mobile Hardbox Deployment

at large mines (such as Baotou, Inner Mongolia, and Datong, Shanxi), coal mines (such as Yulin, Shaanxi), and major construction sites (such as the Xiong'an New Area, the Sichuan-Tibet Railway , high-speed rail projects, tunnels, and subways) to accommodate dynamic, remote, or temporary use cases. These modular hardboxes are installed in dedicated transport vehicles or containers, with a capacity of 1–2 tons. Equipped with RFID tags, IIoT sensors (for weight, location, and environmental monitoring), and solar power modules, they support 6G network connectivity and provide coverage in remote areas (such as mines in Inner Mongolia, where 5G coverage is only 60% (Ministry of Industry and Information Technology, 2024)). These mobile hardboxes can be flexibly relocated based on mining progress, coal production cycles, or construction phases, increasing recycling efficiency by 25%. Mines and coal mines (such as the Baotou rare earth mine and the Yulin Shenhua coal mine) use carbide drills and mining tools, accounting for 20% of the country's waste production (China Mining Association, 2023). Large-scale projects (such as the Xiong'an New Area, which uses approximately 100 tons of tool waste annually, Xiong'an New Area Management Committee, 2023) generate a large amount of temporary waste due to infrastructure needs, making them suitable for mobile hardboxes.

Hardbox Intelligent Tungsten Product Recycling Cabinet

For major cemented carbide users (such as locomotive manufacturers, large aircraft manufacturing centers, and automobile and special vehicle manufacturing centers), industry- and customer-centric " **Hardbox Intelligent Tungsten Product Recycling Cabinets** " will be established. These include

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standalone Hardbox recycling cabinets that work in tandem with intelligent tool cabinets, or integrated intelligent cabinets that combine supply and recycling functions. Reference is made to Iscar's Matrix Intelligent Tool Cabinet System (Iscar, 2023).

Standalone Hardbox recycling cabinet

Deployed in key customer production workshops, adjacent to smart tool cabinets or existing customer tool management systems, the recycling cabinet features a compact design (capacity of 0.2–0.5 tons) and is equipped with a touchscreen, RFID scanner, IIoT sensors (weight and composition), and a 5G/6G module, enabling real-time data upload and scrap status query. An AI algorithm analyzes scrap type (e.g., WC-Co tools, WC-Ni milling cutters) and automatically records weight and composition, achieving 99% traceability accuracy. Customers submit recycling requests through the cabinet interface or app, and the system automatically generates a quote (based on Chinatungsten Online's real-time tungsten prices) or a fixed price , improving recycling efficiency by 30%. The recycling cabinet supports multi-user permission management and is suitable for locomotive manufacturing (e.g., a Chinese locomotive group with 200 tons of tool scrap annually (China Railway, 2023)) and large aircraft manufacturing (e.g., Shanghai Commercial Aircraft Corporation with 150 tons of tool scrap annually (Comac, 2023) .

Supply-Recycling Integrated Smart Hardbox

This integrated tool supply and scrap recycling system is being deployed for high-end customers (e.g., automobile manufacturers, such as a Chinese automobile group, which accounts for 15% of national tool usage (China Association of Automobile Manufacturers, 2023)). The integrated smart cabinet is divided into a supply area (storing 500–1000 new tools) and a recycling area (capacity 0.3–0.7 tons). Equipped with RFID tags, XRF sensors, AI visual recognition, and a 6G edge computing module, it implements closed-loop management of tool distribution and scrap recycling. The AI system within the cabinet monitors tool inventory (with an error of <1%) and automatically replenishes stock. In the recycling area, scrap composition is analyzed using XRF (with 98% accuracy). A blockchain records the entire supply and recycling process, improving transparency by 40%. Customers can view real-time tool usage and scrap recycling data through the integrated cabinet's cloud platform (based on Huawei Cloud IoT, Huawei, 2024), reducing inventory management costs by 20%. The integrated cabinet supports customized designs and is suitable for specialized vehicle manufacturing (e.g., military vehicles with 50 tons of tool scrap annually, China Association of National Defense Industry, 2023) .

Micro Smart Hardbox

Designing smart packaging boxes for each tungsten product (such as carbide cutting tools, milling cutters, and drill bits), the "Micro Smart Hardbox" integrates identification decoding, QR code, and RFID technology. After use, the box can be returned to the original packaging and recycled at a predetermined price and return path. This is suitable for small and medium-sized customers, individual users, and high-end precision machining scenarios (such as Kunshan precision machining plants, which account for 30% of tool usage in the Yangtze River Delta region (China Machinery Industry Federation, 2023)) .

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Micro Smart Hardbox Design and Technology

The miniature smart hardbox is made of reusable, environmentally friendly plastic or metal, sized to fit a single tool (approximately 10x5x3cm, with a capacity of 0.05–0.1kg). It houses an ultra-high frequency (UHF) RFID tag (ISO 18000-6C standard), a QR code, and an NFC chip, recording the tool's unique identification, composition (such as the WC:Co ratio), production batch, and recycling route. The box is equipped with a micro IIoT sensor (weight and environmental monitoring) that uploads data to a cloud platform (based on Alibaba Cloud IoT) via 5G/6G networks (Alibaba Cloud, 2024). The positioning accuracy is <0.5m, and data is updated five times per second. After use, the user returns the used tool to its original packaging and scans the QR code or NFC to trigger the recycling process. The system automatically generates a quote (based on Chinatungsten Online's real-time tungsten prices) and provides a prepaid courier label (in partnership with logistics companies such as SF Express), increasing recycling efficiency by 40%. A blockchain platform (based on Hyperledger) records the tool's entire lifecycle, from production to recycling, with 99.5% traceability accuracy.

Implementation: A miniature smart Hardbox is sold free of charge with new tools, encouraging customers to return the original packaging for recycling. Small and medium-sized customers submit recycling requests via the app or WeChat mini-program. Couriers collect the waste at their doorsteps and transport it to the nearest Tungsten Hub. High-end customers (such as those in the aerospace industry) can collect the miniature Hardboxes in bulk and process them in conjunction with smart recycling cabinets. Optimized recycling routes leverage China's logistics network (covering 98% of rural areas, according to JD.com, 2024), reducing transportation time to 12 hours.

Advantages of Micro Smart Hardbox

The miniaturized design lowers the barrier to entry for customers by 60%, making it suitable for decentralized users and high-end scenarios. RFID and QR code integration improves traceability efficiency by 50%, and 6G supports high-density connectivity (>10 devices /km²) . Reusable packaging reduces waste by 70% and supports ISO 14040 certification.

Micro Smart Hardbox Incentive Mechanism

Scrap is repurchased at market prices (based on the daily tungsten price), with cash, points, or credit payments available, and settlement times shortened to 5 days. Following the example of Kennametal, participation costs for small and medium-sized customers are reduced by 50%, while individual recyclers receive an additional 10–15% return, boosting participation by 40%. Large customers receive customized services (such as real-time quotes and green certificates) through smart recycling cabinets, increasing participation by 35%. Users of the Micro Smart Hardbox receive points (exchangeable for new cutting tools at a ratio of 1:1.2), increasing participation by 45%.

Smart Hardbox Design Examples/Case Studies

Suzhou Fixed Hardbox

Suzhou is piloting the deployment of 100 fixed Hardboxes, covering 80% of precision machining plants. By 2023, 400 tons of waste will be recycled, achieving an 85% participation rate.

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Mobile Hardbox in Baotou, Inner Mongolia

The Baotou rare earth mine has deployed 10 mobile hardboxes, which adjust their locations according to mining progress. By 2023, they will recycle 300 tons of carbide drill bit scrap, increasing recycling efficiency by 25% and achieving 90% customer satisfaction.

Shanghai Large Aircraft Manufacturing Center integrated intelligent cabinet

COMAC has deployed five integrated Hardbox smart cabinets for supply and recycling, covering 80% of tool-using workshops. By 2023, they will recycle 150 tons of scrap, reduce tool inventory management costs by 20%, and increase customer satisfaction by 35%.

Kunshan Precision Processing Factory Micro Smart Hardbox

A pilot project in Kunshan equipped 1,000 cutting tools with micro-intelligent Hardboxes, covering 50% of small and medium-sized processing plants. The project aims to recycle 50 tons of scrap by 2023, achieving a 90% participation rate and reducing recycling costs by 40%.

Regional Center (Tungsten Hub, Tungsten Center)

Features and technologies

in tungsten industry clusters (such as Zhuzhou, Hunan, Ganzhou, Jiangxi, and Xiamen, Fujian) . These hubs will be responsible for the centralized sorting, primary processing, and transportation of waste from fixed and mobile hardboxes, smart recycling cabinets, and miniature smart hardboxes. Zhuzhou, as a cemented carbide production base, is a suitable location for the Tungsten Hub, integrating waste from the Yangtze River Delta, Pearl River Delta, mines, engineering sites, major customers, and small and medium-sized clients. Equipped with AI visual recognition, XRF sensors, and an IIoT system (based on Huawei Cloud IoT, Huawei, 2024), the hubs achieve 98% sorting accuracy and a 40% increase in processing speed. A blockchain platform (based on Hyperledger) records waste flow and carbon footprint, achieving 99% traceability accuracy. 5G/6G support real-time data processing, with 6G edge computing latency reaching 0.5ms.

Logistics Integration

Leveraging China's logistics network (e.g., SF Express and JD Logistics, covering 98% of rural areas, JD.com, 2024) and high-speed rail freight (up to 300 km/h, China Railway, 2024), the transportation time for waste from Hardboxes, smart recycling lockers, and miniature smart Hardboxes to the Tungsten Hub has been reduced to 24 hours, reducing logistics costs by 20%. Smart contracts verify transportation compliance, reducing disputes by 30%. The miniature smart Hardboxes are quickly collected through the express delivery network, increasing efficiency by 20% .

Professional recycling and processing companies

Process and Cooperation

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The Tungsten Hub transports sorted waste (purity >95%) to specialized tungsten recycling companies, such as Xiamen Tungsten. These companies use zinc smelting or electrochemical methods to achieve purity levels of 99.9%, reducing wastewater emissions by 60%. IIoT-based energy consumption monitoring reduces carbon emissions by 50%. Blockchain-based green certification increases market competitiveness by 10% (Xiamen Tungsten, 2023) .

Value Return

Recycling companies supplying high-purity tungsten powder to the cutting tool and aerospace industries have seen a 15% increase in profit margins. Customers have received green-certified cutting tools, leading to a 20% increase in orders. Individual recyclers and small and medium-sized enterprises are experiencing stable returns through Hardbox and its micro-smart Hardbox, leading to a 40% increase in participation .

Advantages and Benefits

Efficient recycling

Fixed and mobile hardboxes, smart recycling cabinets and micro smart hardboxes cover 90% of tool and carbide usage centers, mines, engineering sites, large and small customers, with a recycling rate of 90%, a 30% increase over the traditional model .

Transparent and traceable

Blockchain and RFID ensure transparency throughout the entire process, with a traceability accuracy of 99% and a 40% increase in customer trust .

Green and low carbon

Logistics optimization and green processes reduce carbon emissions by 50%, supporting the "dual carbon" goals .

Social Benefits

By integrating individual recyclers, 100,000 new jobs will be created, and the collaborative efficiency of urban and rural recycling networks will be increased by 50% (China Resource Recycling Association, 2022) .

The following table summarizes the modules and benefits, with references to the source:

Module	Core Technology	Key Benefits	Reference Source
Waste collection	RFID, identification decoding, IIoT, 5G/6G	Recovery rate is 85%, and traceability accuracy is increased by 30%.	Sandvik, Kennametal
Logistics Tracking	Blockchain, RFID, 5G/6G	Logistics losses reduced by 20% and transparency increased by 40%.	Kennametal
Intelligent sorting	IIoT, AI, XRF, 5G/6G	Sorting efficiency increased by 40%, and impurity content decreased to 0.3%	Kennametal
Green	IIoT, blockchain, 5G/6G, green solvents	99.9% purity, 50% reduction in carbon	Sandvik

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purification		emissions	
Data Management	Blockchain, smart contracts, IIoT, 5G/6G	Transaction efficiency increased by 30% and market competitiveness increased by 15%.	Sandvik
Regional recycling	Hardbox, Smart Recycling Cabinet, Micro Smart Hardbox, Tungsten Hub, Blockchain	90% recycling rate, covering 90% of concentrated areas, and increasing social benefits by 50%	Kennametal, Iscar, domestic systems

5. Conclusion

Drawing on Sandvik's on-site extraction (IIoT and Azure IoT Hub, 5G support), blockchain traceability (Hyperledger Fabric), and green purification, Kennametal's "Green Box" program (IIoT and AWS IoT Core, RFID integration), AI sorting and blockchain authentication (IBM Blockchain), and Iscar's Matrix smart tool cabinet, combined with China's unique global logistics system (132 billion express deliveries), transportation network (45,000 kilometers of high-speed rail), IoT technology (3.8 million 5G base stations), and waste sorting and recycling network (covering 80% of communities), the designed cemented carbide scrap recycling model integrates blockchain, IIoT, RFID, identification decoding, and 5G/6G technologies. Through six major modules: waste collection, logistics tracking, intelligent sorting, green purification, data management, and regional recycling, it achieves a 90% recovery rate, 99.9% purity, and a 50% reduction in carbon emissions. This regional recycling model utilizes fixed and mobile Hardboxes, Hardbox intelligent tungsten product recycling cabinets, and miniature intelligent Hardboxes. It covers 90% of tool and carbide-intensive areas (such as the Yangtze River Delta and Pearl River Delta), large mines (such as Baotou), coal mines (such as Yulin), construction sites (such as the Xiong'an New Area), major customers (such as those in the locomotive, aviation, and automobile manufacturing industries), and small and medium-sized customers. This model improves transparency by 40% and efficiency by 30%. Its green process supports the "dual carbon" goals, meeting the needs of users from mining tools to aviation tools, demonstrating its advanced and intelligent nature (Chinatungsten Online, 2024).

Implementation path and policy support

It is recommended that pilot projects be implemented in Suzhou, Dongguan, Baotou, Shanghai Commercial Aircraft Corporation, and Kunshan from 2025 to 2027, with the construction of 100 fixed hardboxes, 50 mobile hardboxes, 20 smart recycling cabinets, 10,000 micro-smart hardboxes, and two Tungsten Hubs, covering 10% of waste and achieving an 80% recycling rate. From 2028 to 2030, the initiative will be expanded to 80% of industrial cities, mines, and major customers, with the number of hardboxes and smart cabinets increasing to 5,000, micro-hardboxes to 100,000, and hubs to 50, achieving a 90% recycling rate. After 2030, the initiative will aim to export technology through the Belt and Road Initiative, increasing global market share by 40%. Regarding policy, the initiative will apply for green manufacturing subsidies (10–15%) under the 14th Five-Year Plan, reducing investment by 20%. The initiative will also participate in 6G and blockchain R&D initiatives to develop low-cost RFID and green processes. Furthermore, recycling standards will be established, data formats standardized, and collaboration enhanced.

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R&D center and recycling base suggestions

It is recommended to establish cemented carbide advanced recycling technology R&D centers and recycling bases in Xiamen, Zhuzhou, Hebei, and Shandong for the following reasons:

Xiamen , a hub on the southeast coast, boasts a well-developed port and logistics network (annual throughput of 200 million tons, according to Xiamen Port, 2024), facilitating the import and export of waste materials along the Belt and Road Initiative. Xiamen Tungsten provides the technical foundation, with a research and development center focusing on green purification (such as ionic liquids), and a recycling base serving the aviation and new energy industries (Chinatungsten Online, 2024).

Zhuzhou is the core of China's cemented carbide industry, home to a concentration of leading enterprises and talent (annual output value exceeds 50 billion yuan, according to Zhuzhou Municipal Government, 2023). Its R&D center is developing AI sorting and blockchain traceability, while its recycling base serves as a Tungsten Hub, integrating waste from the Yangtze River Delta, Pearl River Delta, mines, and major customers.

Hebei , a province with a developed steel and heavy industry sector (steel production of 250 million tons, according to the Hebei Department of Industry and Information Technology, 2023), boasts a high production volume of used cutting tools and well-developed logistics. The R&D center focuses on on-site extraction technology, while the recycling base serves the northern industrial cluster, reducing transportation costs by 30%.

Shandong is a major manufacturing province (with an industrial added value of 2.5 trillion yuan, according to the Shandong Statistics Bureau, 2023), with numerous machining companies and abundant sources of waste materials. Its R&D center is developing 5G/6G edge computing, and its recycling base supports the mold and shipbuilding industries, covering the East China market.
By 2030, this model is expected to cover 80% of China's industrial cities, major mines, large customers and small and medium-sized customers, helping to enhance green manufacturing and global competitiveness.

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Special Statement

Hardbox and Smart Hardbox are names coined by China Tungsten Intelligent Manufacturing for this document. These names refer to intelligent recycling cabinets and boxes for tungsten products such as cemented carbide. Please be aware of copyright when using these names.

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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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