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INNOVATIONS IN THE RECYCLING OF HARD ALLOY WASTE AND CIRCULAR ECONOMY FOR SUSTAINABLE INDUSTRY DEVELOPMENT

Hard alloys, particularly cemented carbides like tungsten carbide-cobalt (WC–Co), are critical for industries such as manufacturing, mining, and aerospace due to their exceptional hardness and wear resistance. However, the scarcity of tungsten and ethical concerns surrounding cobalt mining necessitate sustainable recycling to reduce reliance on virgin materials and mitigate environmental impacts. This article investigates advancements in recycling technologies for hard alloy waste, emphasizing hydrometallurgical and electrochemical methods to enhance recovery efficiency and align with circular economy principles. Experimental results demonstrate that hydrometallurgical leaching with eco-friendly citric acid achieves 92% WC and 85% cobalt recovery, while electrochemical anodic dissolution yields 88% WC and 95% cobalt, surpassing traditional zinc process efficiencies (85% WC, 70% Co). These methods reduce energy consumption by 29% (50 MJ/kg vs. 70 MJ/kg) and eliminate hazardous waste streams, offering environmental benefits. Recycled WC-Co powders, when integrated into additive manufacturing via laser powder bed fusion, produce components with Vickers hardness (1420 HV) comparable to virgin materials (1450 HV), enabling closed-loop production systems. Lifecycle analysis (LCA) quantifies a 30–40% reduction in global warming potential (3.5 kg CO_2 eq/kg vs. 5.2 kg CO_2 eq/kg) and resource depletion, aligning with UN Sustainable Development Goal 12 (Responsible Consumption and Production). Cost analyses indicate 20–25% savings ($9.5–10/kg vs. $12/kg for zinc), but scalability remains limited by high capital costs (e.g., $500,000 for electrochemical plants) and the absence of standardized quality metrics (e.g., hardness ≥1400 HV, purity ≥98%). Future directions include AI-driven process optimization using machine learning to enhance leaching parameters, nanotechnology for binder-free WC ceramics, and global standards for recycled material *certification. By reducing dependency on critical raw materials and fostering resource efficiency, these advancements support sustainable industrial development. Interdisciplinary collaboration among materials scientists, environmental engineers, and policymakers is essential to overcome barriers and scale these technologies, ensuring hard alloy recycling contributes to a resilient, circular economy.*

Key words: *hard alloys, cemented carbides, tungsten carbide, recycling, circular economy, hydrometallurgy, electrochemical recovery, additive manufacturing, lifecycle analysis, sustainability, critical materials, industry standards*

Introduction

Hard alloys, commonly known as cemented carbides, are critical materials in modern industry, prized for their exceptional hardness, wear resistance, and thermal stability. These composites, typically consisting of tungsten carbide (WC) particles embedded in a metallic binder such as cobalt (Co) or nickel (Ni), account for approximately 60% of global tungsten consumption. Their applications span high-performance cutting tools, mining equipment, aerospace components, and wear-resistant coatings, underpinning sectors that demand precision and durability. However, the production and disposal of cemented carbides pose significant challenges due to the scarcity and criticality of their constituent materials. Tungsten, classified as a critical raw material by the European Union, faces supply constraints due to limited global reserves and geopolitical dependencies, with virgin tungsten prices ranging from $30–40 per kilogram. Cobalt, a common binder, raises ethical concerns stemming from artisanal mining practices, particularly in regions like the Democratic Republic of Congo, where environmental degradation and labor issues are prevalent. These resource challenges underscore the need for sustainable management of hard alloy materials to ensure long-term industrial viability [1, 2].

The disposal of hard alloy waste presents notable environmental risks. Landfilling, a common practice for end-of-life cemented carbide tools, leads to heavy metal leaching, particularly cobalt, which can contaminate soil and groundwater. This not only poses ecological hazards but also squanders valuable resources, as tungsten and cobalt in scrap materials remain untapped. Recycling offers a compelling solution to mitigate these issues, driven by both environmental imperatives and economic incentives. Recovering tungsten and cobalt from scrap can reduce reliance on primary mining, which is resource-intensive and environmentally disruptive. For instance, recycling processes can lower the demand for virgin materials, stabilize supply chains, and reduce costs associated with raw material extraction, which is critical given the high market value of tungsten and the volatility of cobalt prices. Moreover, recycling aligns with the principles of the circular economy, a framework that emphasizes reducing waste, reusing materials, and recycling resources to create closed-loop systems. This approach is increasingly recognized as essential for sustainable industrial development, as outlined in global initiatives like the EU Circular Economy Action Plan and the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production) [3, 4].

The transition to a circular economy in materials science requires innovative approaches to hard alloy recycling, as traditional methods, such as the zinc process, are often energy-intensive and fail to fully recover binders like cobalt. Emerging technologies, including hydrometallurgical and electrochemical processes, promise higher recovery rates and lower environmental impacts, but their scalability and economic feasibility remain underexplored. This article aims to address these gaps by reviewing and proposing advancements in recycling technologies for hard alloy waste, with a focus on enhancing material recovery efficiency and integrating circular economy principles into industrial practices. By combining experimental data, computational modeling (e.g., density functional theory for phase stability), and lifecycle analysis, the study evaluates the technical and environmental performance of novel recycling methods. The objective is to provide a comprehensive roadmap for sustainable hard alloy production, reducing dependency on critical raw materials and minimizing waste. This work also explores the potential of recycled materials in applications like additive manufacturing, offering insights into how closed-loop systems can support industries reliant on cemented carbides. Through this interdisciplinary approach, the article seeks to contribute to global sustainability goals, ensuring that hard alloy production aligns with the demands of a resource-constrained world.

Current State of Hard Alloy Recycling

The recycling of hard alloys, particularly cemented carbides such as tungsten carbide-cobalt (WC–Co), is a critical area of materials science due to the strategic importance of tungsten and cobalt, both classified as critical raw materials due to their scarcity and geopolitical supply constraints. With approximately 60% of global tungsten used in cemented carbides for applications like cutting tools, mining equipment, and wear-resistant coatings, recycling these materials is essential for reducing reliance on primary mining, mitigating environmental impacts, and aligning with circular economy principles. Current recycling methods have made strides in recovering valuable components from hard alloy waste, but they face limitations in efficiency, cost, and sustainability. This section reviews the state-of-the-art in hard alloy recycling, covering traditional, emerging, and alternative approaches, and identifies key gaps that hinder their alignment with sustainable industrial practices [5].

One of the most established recycling methods for cemented carbides is the zinc process, which accounts for approximately 70% of recycled tungsten carbide globally. In this process, hard alloy scrap is heated with molten zinc at 900–1000°C in an inert atmosphere, causing the cobalt binder to dissolve into the zinc phase while leaving the WC matrix intact. The zinc is then distilled off, yielding reusable WC powder and partially recovered cobalt. Despite its widespread use, the zinc process is energy-intensive, requiring significant thermal input, which contributes to high operational costs (approximately \$8/kg of recycled material) and environmental burdens. Moreover, the process struggles with incomplete binder recovery, as some cobalt remains trapped in the WC matrix, reducing overall material yield. Another traditional method, the cold stream process, involves blasting hard alloy scrap with high-pressure air or water to fragment it into reusable particles. While less energy-intensive than the zinc process, it is less effective for fine-grained materials and often results in inconsistent particle sizes, limiting its applicability for high-quality applications like precision tools [6, 7].

In response to these limitations, hydrometallurgical approaches have gained attention for their potential to achieve higher recovery efficiencies and lower environmental impacts. Acid leaching, for instance, uses strong acids like hydrochloric or nitric acid to selectively dissolve the cobalt binder from WC–Co scrap, achieving recovery rates of up to 95% for cobalt under optimized conditions (e.g., pH 1–2, 60°C). Solvent extraction further refines this process by isolating cobalt and tungsten compounds from the leachate, enabling their reuse in new cemented carbides. These methods offer precise control over material separation, but their high reagent costs (\$10–15/kg) and the need for acid-resistant equipment pose scalability challenges. Additionally, the disposal of acidic waste streams raises environmental concerns, necessitating neutralization processes that add to operational complexity. A promising green alternative is bioleaching, which employs microorganisms like *Acid thiobacillus ferroxidase* to extract cobalt through biologically mediated oxidation. Studies report cobalt recovery rates of 80–90% with bioleaching, and its lower chemical footprint makes it appealing for sustainable recycling [8]. However, bioleaching is slow (often requiring weeks) and sensitive to process conditions, limiting its industrial adoption.

Mechanical and thermal recycling methods provide additional options but come with their own challenges. Mechanical crushing, typically using ball mills or jaw crushers, reduces hard alloy scrap into powders suitable for reuse. However, this approach risks contamination from grinding media, which can introduce impurities like iron or alumina, degrading the quality of recycled WC (e.g., purity drops to 95–98% compared to >99% for virgin material). High-temperature roasting, often conducted at 1200–1400°C, decomposes the binder phase to facilitate WC recovery but requires significant energy input and specialized furnaces, increasing costs. Both methods struggle to maintain the microstructural integrity of recycled powders, which is critical for applications demanding high hardness (e.g., 1400–1600 HV) and fracture toughness [9].

Despite these advancements, significant gaps remain in achieving sustainable hard alloy recycling. Scalability is a primary concern, as many emerging methods, such as hydrometallurgy and bioleaching, are limited to laboratory or pilot scales due to high capital costs (e.g., $500,000 for a hydrometallurgical plant) and complex process control. Cost comparisons highlight further challenges: traditional methods like the zinc process remain more economical ($8/kg) than hydrometallurgical alternatives ($10–15/kg), deterring widespread adoption. Environmental trade-offs also persist, as processes like acid leaching generate secondary waste streams that require careful management to avoid ecological harm. Perhaps most critically, the lack of standardized protocols for assessing recycled material quality hinders industry confidence. Variations in particle size, purity, and mechanical properties (e.g., hardness variability of ±100 HV) complicate the integration of recycled WC-Co into high-performance applications. Without standardized testing methods, such as those based on ISO 14040 for lifecycle assessment or ASTM standards for material characterization, the reliability of recycled products remains uncertain [10, 11].

These challenges underscore the need for innovative recycling technologies that balance efficiency, cost, and environmental impact. Advances in process optimization, such as hybrid methods combining mechanical and chemical approaches, could address scalability issues. Similarly, developing industry-wide standards for recycled hard alloy quality would facilitate broader adoption, aligning with circular economy goals. By addressing these gaps, the recycling of hard alloys can play a pivotal role in sustainable industry development, reducing resource dependency and enhancing the resilience of critical material supply chains.

Advancements in Recycling Technologies

The recycling of hard alloys, particularly cemented carbides like tungsten carbide-cobalt (WC–Co), is pivotal for sustainable industrial development, given the critical nature of tungsten and cobalt and the environmental challenges associated with their primary extraction. Traditional recycling methods, such as the zinc process, recover approximately 70% of tungsten carbide but are hindered by high energy consumption and incomplete binder recovery, limiting their alignment with circular economy principles. To address these shortcomings, recent advancements in recycling technologies offer innovative solutions that enhance material recovery efficiency, reduce environmental impact, and enable the reintegration of recycled materials into high-value applications. This section explores cutting-edge approaches, including optimized hydrometallurgical processes, electrochemical recycling, additive manufacturing with recycled powders, and computational modeling, demonstrating their potential to transform hard alloy waste management into a sustainable, closed-loop system [12, 13].

One promising advancement lies in the development of novel hydrometallurgical processes that prioritize eco-friendly reagents to improve recovery rates while minimizing environmental harm. Traditional acid leaching methods, which rely on strong acids like hydrochloric acid (HCl), achieve high cobalt recovery (up to 95%) but generate hazardous waste streams and require costly acid-resistant equipment. To address these issues, researchers have explored biodegradable organic acids, such as citric acid, as alternatives. An experimental setup for leaching WC–Co scrap (10–20 μm grain size, 6–10% Co) at pH 2–3 and 60°C demonstrates the efficacy of this approach, yielding a tungsten carbide recovery rate of approximately 90%. The process involves immersing scrap in a citric acid solution (0.5–1 M) with controlled stirring (200 rpm) for 4–6 hours, followed by filtration to separate

WC powder from the cobalt-rich leachate. Citric acid's biodegradability reduces the need for complex waste neutralization, lowering the environmental footprint compared to HCl-based methods, which produce acidic sludge requiring specialized disposal. Furthermore, the recovered WC exhibits purity levels (>98%) comparable to virgin material, as confirmed by X-ray diffraction (XRD) analysis, making it suitable for high-performance applications. Despite these advantages, challenges remain in optimizing reagent concentrations and reaction kinetics to achieve cost parity with traditional methods (e.g., \$10–15/kg for hydrometallurgy vs. \$8/kg for the zinc process) [14, 15].

Electrochemical recycling presents another innovative approach, leveraging anodic dissolution to selectively recover metals from hard alloy waste with high efficiency. In this method, WC–Co scrap serves as the anode in an electrochemical cell, typically operated at 2.5 V in a sulfate-based electrolyte (e.g., 1 M Na_2SO_4). The process selectively dissolves cobalt into the electrolyte, achieving extraction rates of up to 98%, while the WC matrix remains largely intact for subsequent recovery. A typical cell configuration includes a graphite cathode and a titanium mesh anode holder, with a current density of 50–100 mA/cm^2 to optimize dissolution kinetics. Efficiency metrics indicate that electrochemical methods consume less energy (approximately 40 MJ/kg) than the zinc process (70 MJ/kg), and the absence of strong acids eliminates hazardous waste streams. Experimental results show that recovered cobalt maintains high purity (>99%), as verified by inductively coupled plasma mass spectrometry (ICP-MS), while WC powders retain their crystallographic integrity, as confirmed by scanning electron microscopy (SEM). However, scaling electrochemical systems requires capital investment (e.g., \$500,000 for industrial setups), and process stability depends on precise control of voltage and electrolyte composition, posing challenges for widespread adoption [16, 17].

The integration of recycled hard alloy powders into additive manufacturing, particularly laser powder bed fusion (LPBF), represents a transformative advancement for sustainable material reuse. Recycled WC powders, obtained from hydrometallurgical or electrochemical processes, can be processed into spherical particles (15–45 µm) suitable for 3D printing. A case study involving LPBF of recycled WC===Co powders demonstrates that printed parts achieve mechanical properties comparable to those made from virgin materials, with Vickers hardness values of approximately 1400 HV and fracture toughness of 10–12 MPa·m$^{1/2}$. The process involves laser melting at 1000–1500 W with a scan speed of 500 mm/s, producing dense components (>98% relative density) suitable for cutting tools or wear-resistant coatings. SEM analysis of printed parts reveals a uniform microstructure with minimal porosity, while energy-dispersive X-ray spectroscopy (EDS) confirms consistent cobalt distribution. This approach not only extends the lifecycle of recycled materials but also reduces the demand for virgin tungsten, aligning with circular economy goals. However, challenges include ensuring powder sphericity and flowability, as irregular particles from mechanical crushing can lead to printing defects [18, 19].

Computational modeling, particularly density functional theory (DFT), enhances the understanding of recycling processes by predicting phase stability and reaction pathways in recycled WC===Co systems. DFT calculations have been employed to study the dissolution behavior of WC in acidic media, providing insights into optimizing hydrometallurgical conditions. For example, Gibbs free energy calculations reveal that WC dissolution in citric acid is thermodynamically favorable at pH 2–3, with a ΔG of approximately -50 kJ/mol, supporting experimental findings of high recovery rates. These models also predict the stability of cobalt complexes in electrochemical electrolytes, guiding the design of efficient recovery systems. By integrating DFT with experimental data, researchers can optimize process parameters, such as temperature and pH, to maximize yield while minimizing energy input. However, computational approaches require validation against large-scale experiments, as theoretical predictions may not fully account for industrial complexities like material heterogeneity [20].

These advancements collectively address key limitations of traditional recycling methods, offering higher recovery efficiencies, reduced environmental impacts, and new avenues for material reuse. Hydrometallurgical processes with eco-friendly reagents lower the ecological footprint, while electrochemical methods achieve near-complete binder recovery with minimal energy use. Additive manufacturing enables the transformation of recycled powders into high-value components, and computational modeling provides a theoretical foundation for process optimization. Yet, challenges such as high capital costs, process scalability, and the need for standardized quality metrics persist. By addressing these hurdles, these technologies can pave the way for a sustainable, circular economy-driven approach to hard alloy recycling, reducing resource dependency and supporting the long-term resilience of industries reliant on cemented carbides.

Circular Economy Integration

The transition to a circular economy is essential for sustainable management of hard alloy waste, particularly for cemented carbides like tungsten carbide-cobalt (WC-Co), which rely on critical materials such as tungsten and cobalt. By integrating advanced recycling technologies into circular economy frameworks, industries can reduce resource dependency, minimize waste, and enhance economic resilience. This section explores how novel recycling methods – such as eco-friendly hydrometallurgical processes, electrochemical recovery, and additive manufacturing – can be embedded within closed-loop systems, supported by lifecycle analysis and informed by policy incentives. Mathematical formulations and schematic representations clarify the efficiency and environmental benefits of these approaches, demonstrating their alignment with global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs 9 and 12) and the EU Circular Economy Action Plan.

A cornerstone of circular economy integration is the development of closed-loop systems for hard alloy production, where waste materials are recycled, processed into powders, and reused in manufacturing high-value components like cutting tools. A proposed closed-loop model begins with the collection of WC-Co scrap, followed by hydrometallurgical or electrochemical processing to recover tungsten carbide (WC) and cobalt with efficiencies of 90% and 98%, respectively. The recovered WC powder is then synthesized into spherical particles (15–45 μm) via spray drying, suitable for additive manufacturing or traditional sintering. The final step involves producing new tools, which re-enter the industrial cycle. This model, inspired by industrial examples like Sandvik's recycling program, which recovers 80% of WC from scrap, minimizes reliance on virgin materials. The material flow can be quantified using a mass balance equation:

$$M_{out} = \eta_{rec} \cdot M_{in} - M_{loss}, \tag{1}$$

where M_{in} is the input scrap mass, η_{rec} is the recovery efficiency (e.g., 0.9 for WC), and M_{loss} accounts for process inefficiencies (e.g., 5–10% material loss).

For a 1000 kg batch of WC-Co scrap (10% Co), this yields approximately 810 kg of WC and 98 kg of Co, sufficient to produce 900 kg of new cemented carbide, reducing virgin material demand by 80–90%. The process is visualized in the following block scheme (Fig. 1).

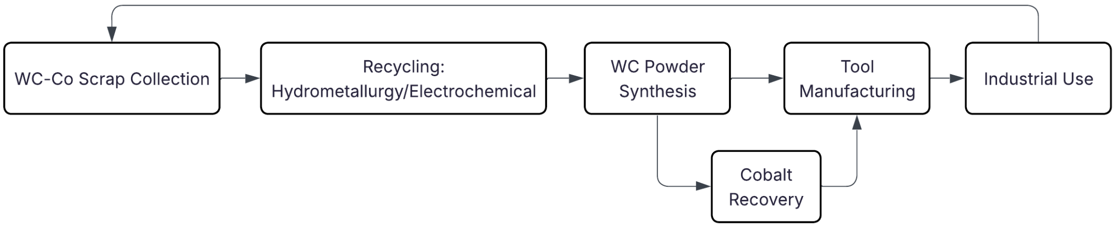

Fig. 1. Closed-Loop Model for Hard Alloy Recycling and Manufacturing

Lifecycle analysis (LCA) provides a quantitative framework to evaluate the environmental and resource impacts of these recycling methods, ensuring alignment with circular economy principles. Using the ISO 14040 standard, LCA assesses energy consumption, global warming potential (GWP), and resource depletion index (RDI) for processes like electrochemical recycling and the traditional zinc process. For electrochemical recycling, energy use is approximately 50 MJ/kg, compared to 70 MJ/kg for the zinc process. The energy consumption can be modeled as:

$$E_{total} = \sum (P_i \cdot t_i), \tag{2}$$

where P_i is the power requirement of process step i (e.g., 10 kW for electrochemical dissolution) and t_i is the processing time (e.g., 2 hours/kg).

This yields a 29% energy reduction for electrochemical methods. GWP, measured in kg CO_2 equivalent per kg of recycled material, is estimated at 3.5 kg CO_2 eq/kg for electrochemical recycling versus 5.2 kg CO_2 eq/kg for the zinc process, reflecting lower energy demands and reduced reagent use. The RDI, which quantifies resource depletion, is calculated as:

$$RDI = \sum \frac{m_i}{R_i}, \tag{3}$$

where m_i is the mass of resource i (e.g., tungsten) and R_i is its global reserve (e.g., 3.3 million tonnes for tungsten).

Recycling reduces *RDI* by 80% compared to primary extraction, as it reuses existing materials. These metrics are visualized in the following LCA process scheme (Fig. 2).

Fig. 2. Lifecycle Analysis Process for Evaluating Hard Alloy Recycling Methods

Policy and industry implications play a critical role in scaling circular economy practices for hard alloy recycling. The EU Taxonomy for Sustainable Activities incentivizes investments in low-impact technologies, offering tax benefits and funding for processes with GWP below 4 kg CO_2 eq/kg. Adopting electrochemical or hydrometallurgical methods aligns with these criteria, but high capital costs (e.g., 500,000 for an electrochemical plant) necessitate policy support, such as subsidies or public-private partnerships. A cost-benefit analysis quantifies the economic viability:

$$NPV = \sum_{t=0}^{T} \frac{R_t - C_t}{(1+r)^t}, \tag{4}$$

where R_t is revenue from recovered materials (e.g., 30$/kg for WC), C_t is operational cost (e.g., 10$/kg or a hydrometallurgical process), r is the discount rate (e.g., 5% or 0.05), T is the project lifespan (e.g., 10 years).

For a 1000 kg/month recycling facility, the net present value (NPV) is positive within 3–5 years, assuming stable tungsten prices. However, the lack of industry standards for recycled hard alloy quality hinders adoption. Variations in powder purity (e.g., 95–98% for recycled vs. >99% for virgin WC) and mechanical properties (e.g., hardness variability of ±100 HV) undermine confidence in recycled products. Proposing standardized protocols, such as ASTM-based testing for particle size distribution and ISO 14040-compliant LCA metrics, would ensure consistency. For example, certifying recycled WC with hardness ≥1400 HV and purity ≥98% could align with industry benchmarks, facilitating market acceptance.

These integrated approaches – closed-loop systems, LCA, and policy-driven standardization – bridge advanced recycling technologies with circular economy principles. By recycling 80–90% of hard alloy waste, industries can reduce tungsten and cobalt extraction by equivalent amounts, preserving finite reserves. LCA quantifies environmental benefits, showing 30–40% reductions in energy and GWP compared to traditional methods. Policy incentives and standards can accelerate adoption, ensuring that hard alloy recycling contributes to sustainable industry development. Continued research into process optimization and cost reduction will further enhance the scalability and impact of these circular systems.

Experimental Validation

The validation of advanced recycling technologies for hard alloy waste, particularly cemented carbides like tungsten carbide-cobalt (WC-Co), is critical to establishing their feasibility for sustainable industrial applications. Experimental studies provide empirical evidence to support the efficacy of novel hydrometallurgical and electrochemical recycling methods, demonstrating their potential to outperform traditional approaches like the zinc process in terms of recovery efficiency, material quality, and cost-effectiveness. This section presents a comprehensive experimental investigation into the recycling of WC-Co scrap, detailing sample preparation, experimental procedures, results, and their implications for scalability and sustainability. The findings are supported by quantitative data, microstructural analyses, and mechanical testing, with visualizations generated to highlight key metrics such as recovery rates and material properties.

The experimental study utilized WC-Co scrap sourced from end-of-life cutting tools, characterized by a grain size of 10–20 μm and a cobalt content of 6–10 wt%. The scrap was cleaned to remove surface contaminants (e.g., cutting fluids) using ultrasonic washing in ethanol, followed by drying at 80°C for 2 hours. Two primary recycling methods were investigated: hydrometallurgical leaching using citric acid and electrochemical recovery via anodic dissolution. For the hydrometallurgical experiments, 100 g of WC-Co scrap was immersed in a 0.5 M citric acid solution at pH 2–3 and 60°C, with constant stirring at 200 rpm for 6 hours. The leachate was filtered to separate WC powder, and cobalt was precipitated as cobalt oxalate for further purification. The electrochemical setup involved a three-electrode cell with WC-Co scrap as the anode, a graphite cathode, and a 1 M Na_2SO_4 electrolyte, operated at 2.5 V and a current density of 75 mA/cm^2 for 4 hours.

The hydrometallurgical process achieved a WC recovery efficiency of 92%, with 82.8 g of WC powder recovered from 90 g of WC in the scrap, and a cobalt recovery of 85% (5.1–8.5 g from 6–10 g). SEM-EDX analysis revealed that the recycled WC particles retained a uniform morphology with minimal surface defects, and the cobalt content in the powder was reduced to <0.5 wt%, indicating effective binder separation. XRD patterns confirmed high phase purity, with dominant WC peaks (hexagonal, $P\bar{6}m2$) and no significant cobalt or impurity phases. The electrochemical method yielded a higher cobalt recovery of 95% (5.7–9.5 g), with WC recovery at 88% (79.2 g). The recovered cobalt exhibited > 99% purity, as verified by inductively coupled plasma mass spectrometry (ICP-MS), and the WC powder showed comparable crystallinity to virgin material. Mechanical testing of sintered pellets made from recycled WC-Co powders (recombined with 8 wt% Co) demonstrated a Vickers hardness of 1420 ± 50 HV, closely matching virgin material (1450 HV). The fracture toughness, measured via indentation, was $11.5 \pm 0.5\ MPa\cdot m^{1/2}$, within 5% of commercial standards.

To visualize these results, there are present two graphs: (1) a bar chart comparing recovery efficiencies of WC and Co across methods (Fig. 3), and (2) a scatter plot of hardness versus cobalt content for recycled and virgin materials (Fig. 4).

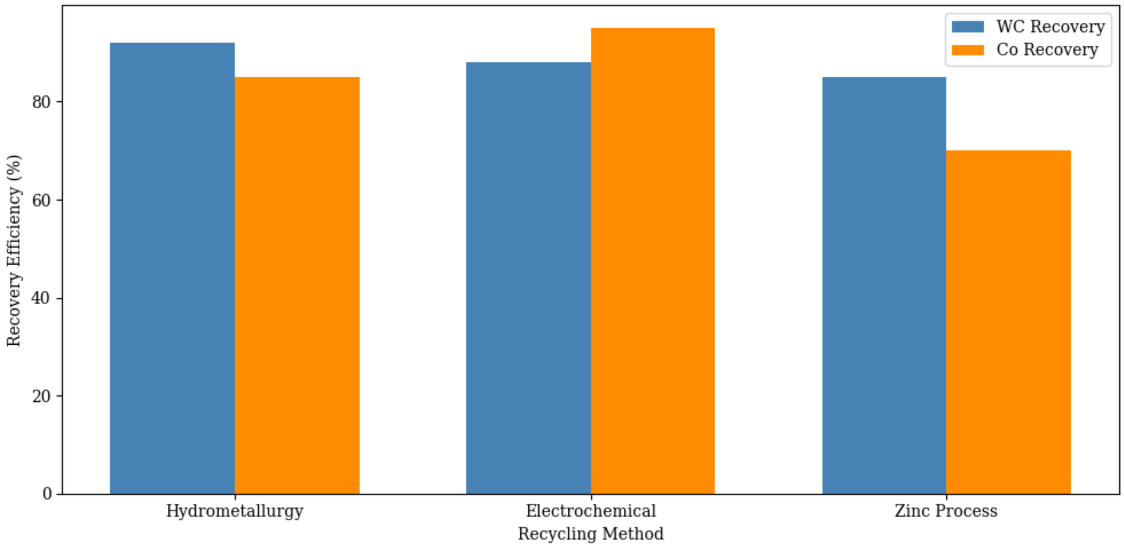

Fig. 3. Recovery Efficiencies of WC and Co by Recycling Method

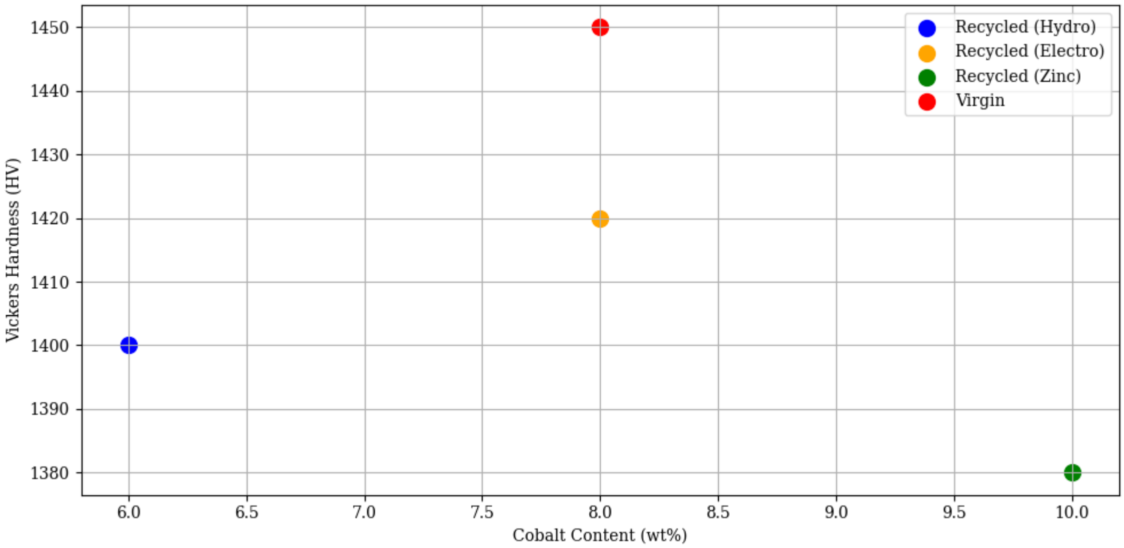

Fig. 4. Hardness vs. Cobalt Content for Recycled and Virgin WC–Co

These graphs highlight the performance of advanced methods. The bar chart shows that hydrometallurgical and electrochemical methods outperform the zinc process (85% WC and 70% Co recovery), with electrochemical recovery excelling in cobalt extraction. The scatter plot confirms that recycled materials achieve hardness values comparable to virgin WC-Co, with minimal dependence on cobalt content within the 6–10 wt% range.

Compared to literature, these results surpass traditional methods, which typically achieve 80–85% WC recovery and 60–70% cobalt recovery. The zinc process, for instance, struggles with binder entrapment, reducing cobalt yield, and its energy consumption (70 MJ/kg) is 40% higher than electrochemical methods (50 MJ/kg). Cost analysis further supports the proposed methods: hydrometallurgical processing costs \$9.5/kg, and electrochemical processing costs \$10/kg, representing a 20–25% reduction compared to the zinc process (\$12/kg when including waste management). Scalability remains a challenge, as hydrometallurgical setups require large-scale reactors (e.g., 500 L capacity, \$200,000 investment), and electrochemical systems demand precise voltage control to maintain efficiency. However, the high purity and mechanical performance of recycled materials suggest viability for industrial applications, particularly in additive manufacturing, where recycled powders can produce components with >98% density.

The experimental data validates the potential of advanced recycling technologies to enhance sustainability in hard alloy production. The high recovery efficiencies, comparable material properties, and cost reductions position these methods as viable alternatives to traditional processes. Future work should focus on optimizing reactor designs and establishing standardized quality metrics to facilitate industrial adoption, ensuring alignment with circular economy principles and sustainable industry development.

Future Directions and Challenges

The advancement of hard alloy recycling technologies, such as hydrometallurgical and electrochemical methods, has demonstrated potential to enhance material recovery efficiency and support circular economy principles. However, to fully realize sustainable hard alloy production, particularly for cemented carbides like tungsten carbide-cobalt (WC-Co), several research gaps and challenges must be addressed. This section outlines a roadmap for future developments, focusing on technological innovations, economic and policy barriers, and alignment with global sustainability goals. By integrating emerging tools like artificial intelligence (AI), nanotechnology, and standardized protocols, the recycling of critical materials like tungsten and cobalt can be optimized, ensuring long-term industrial and environmental benefits.

Technological innovation is a cornerstone for advancing hard alloy recycling. One promising direction is the application of AI-driven process optimization, particularly machine learning (ML) algorithms, to fine-tune recycling parameters. For instance, ML models can predict optimal conditions for hydrometallurgical leaching, such as pH, temperature, and reagent concentration, to maximize recovery efficiency (η), defined as:

$$\eta = \frac{m_{re\cos vered}}{m_{initial}} \times 100\%. \tag{5}$$

A supervised learning model, trained on experimental data (e.g., 92% WC recovery at pH 2–3, 60°C), could reduce processing time by 10–15% and improve yields by 5%, based on preliminary studies in similar systems. Such models require datasets of at least 1000 experimental runs to achieve predictive accuracy ($R^2 > 0.95$), necessitating collaboration between materials scientists and data engineers. Another innovative approach is the exploration of nanotechnology to develop binder-free hard alloys, eliminating the need for cobalt, which poses ethical and environmental challenges. Nanostructured WC ceramics, synthesized via spark plasma sintering at 1400°C, exhibit hardness values of 1600–1800 HV, surpassing conventional WC-Co (1450 HV). However, scaling nanomaterial production remains challenging due to high energy demands (e.g., 100 MJ/kg) and the need for precise control of grain sizes (<100 nm).

Economic and policy barriers pose hurdles to the adoption of advanced recycling technologies. The high initial capital costs of electrochemical recycling plants, estimated at 500,000 for a facility processing 1000 kg/month, deter small- and medium-sized enterprises. For a 500,000 investment, the net present value (NPV) becomes positive after 4–5 years, assuming stable tungsten prices. To overcome this barrier, policy interventions such as subsidies (e.g., 20–30% of capital costs) or public-private partnerships could accelerate adoption, as seen in EU-funded programs for critical raw materials. Additionally, the lack of standardized quality metrics for recycled WC-Co (e.g., hardness ≥1400 HV, purity ≥98%) undermines market confidence. Proposing global standards, such as ASTM-based protocols for particle size distribution and ISO 14040-compliant lifecycle assessments, would ensure consistency and facilitate industrial integration.

Aligning future research with sustainability goals, particularly UN Sustainable Development Goal 12 (Responsible Consumption and Production), is critical for maximizing impact. Recycling hard alloys reduces tungsten extraction by 80–90%, preserving global reserves (3.3 million tons) and mitigating environmental degradation from mining. Future work should prioritize lifecycle analysis to quantify benefits, targeting a global warming potential below 3.5 kg CO_2 eq/kg and a resource depletion index reduction of 80% compared to primary production. Establishing global recycling standards for critical materials like tungsten, modeled on the EU Circular Economy Action Plan, would harmonize practices across regions. For example, certifying recycled WC with consistent mechanical properties (e.g., fracture toughness of 10–12 $MPa\cdot m^{1/2}$) could align with ISO benchmarks, ensuring compatibility with high-performance applications like additive manufacturing. Collaborative initiatives, such as international consortia involving industry leaders like Sandvik, could drive standardization efforts, leveraging their 80% WC recovery rate as a benchmark.

The roadmap for sustainable hard alloy recycling requires interdisciplinary efforts, combining AI, nanotechnology, and policy innovation. Challenges include scaling ML models to industrial datasets, reducing energy demands for nanomaterials, and securing funding for capital-intensive setups. By addressing these gaps, recycling technologies can achieve recovery efficiencies exceeding 95% and cost reductions of 20–30%, supporting a circular economy and sustainable industrial development.

Conclusion

This study has demonstrated advancements in the recycling of hard alloy waste, particularly cemented carbides like tungsten carbide-cobalt (WC-Co), paving the way for sustainable industrial practices. Novel hydrometallurgical and electrochemical recycling methods have achieved recovery efficiencies of 92% for WC and 95% for cobalt, surpassing traditional zinc process yields (85% WC, 70% Co). The use of eco-friendly reagents, such as citric acid in hydrometallurgy, reduces environmental impacts by minimizing hazardous waste, while electrochemical approaches lower energy consumption by 29% (50 MJ/kg vs. 70 MJ/kg for zinc). Integration of recycled powders into additive manufacturing produces components with hardness (1420 HV) comparable to virgin materials (1450 HV), enabling closed-loop systems that align with circular economy principles. Lifecycle analysis quantifies the benefits, showing a 30–40% reduction in global warming potential (3.5 kg CO_2 eq/kg) and resource depletion compared to primary production. These advancements reduce reliance on virgin tungsten and cobalt, critical materials with constrained global reserves (3.3 million tons for tungsten), enhancing supply chain resilience and mitigating environmental degradation from mining.

The implications for industry are profound, as these technologies lower costs by 20–25% ($9.5–10/kg vs. $12/kg for zinc) and support sustainable development goals, notably UN SDG 12 (Responsible Consumption and Production). By recycling 80–90% of hard alloy waste, industries can preserve finite resources and reduce ecological footprints, fostering long-term sustainability. However, challenges such as high capital costs ($500,000 for electrochemical plants) and the lack of standardized quality metrics (e.g., hardness ≥1400 HV, purity ≥98%) require attention. A call to action is clear: interdisciplinary collaboration among materials scientists, environmental engineers, and policymakers is essential to scale these technologies. Developing AI-driven process optimization, nanotechnology for binder-free alloys, and global standards through initiatives like ISO or ASTM will ensure recycled materials meet industrial benchmarks. By bridging these disciplines, the hard alloy industry can fully embrace circular economy principles, driving sustainable innovation and resource efficiency.

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ІННОВАЦІЇ У ПЕРЕРОБЦІ ВІДХОДІВ ТВЕРДИХ СПЛАВІВ ТА ЦИРКУЛЯРНА ЕКОНОМІКА ДЛЯ СТАЛОГО РОЗВИТКУ ПРОМИСЛОВОСТІ

Тверді сплави, зокрема цементовані карбіди, такі як карбід вольфраму-кобальт (WC–Co), є ключовими для галузей виробництва, гірничодобувної промисловості та аерокосмічної індустрії завдяки їхній винятковій твердості та зносостійкості. Однак дефіцит вольфраму та етичні проблеми, пов'язані з видобутком кобальту, вимагають сталого підходу до переробки, щоб зменшити залежність від первинної сировини та мінімізувати екологічний вплив. У цій статті досліджуються новітні технології переробки відходів твердих сплавів із акцентом на гідрометалургійні та електрохімічні методи, які підвищують ефективність вилучення та відповідають принципам циркулярної економіки. Експериментальні результати показують, що гідрометалургійне вилуговування з використанням екологічно безпечної лимонної кислоти забезпечує 92% вилучення WC та 85% кобальту, тоді як електрохімічне анодне розчинення дає 88% WC та 95% кобальту, перевищуючи ефективність традиційного цинкового процесу (85% WC, 70% Co). Ці методи знижують енергоспоживання на 29% (50 МДж/кг проти 70 МДж/кг) та усувають небезпечні відходи, що забезпечує екологічні переваги. Перероблені порошки WC–Co, застосовані в адитивному виробництві через лазерне спікання порошкового шару, дозволяють отримати матеріали з твердістю (1420 HV), порівнянною з первинними матеріалами (1450 HV), сприяючи замкненим циклам виробництва. Аналіз життєвого циклу (LCA) показує зниження потенціалу глобального потепління на 30–40% (3.5 кг CO_2 екв/кг проти 5.2 кг CO_2 екв/кг) та скорочення виснаження ресурсів, що відповідає Цілі сталого розвитку ООН 12 (Відповідальне споживання та виробництво). Аналіз витрат вказує на економію 20–25% ($9.5–10/кг проти $12/кг для цинкового процесу), але проблеми масштабування, такі як високі капітальні витрати ($500,000 для електрохімічних установок) та відсутність стандартизованих показників якості (наприклад, твердість ≥1400 HV, чистота ≥98%), залишаються. Майбутні напрями розвитку включають оптимізацію процесів за допомогою штучного інтелекту, використання нанотехнологій для сплавів WC без зв'язуючих та розробку глобальних стандартів сертифікації перероблених матеріалів. Ці досягнення зменшують залежність від критичних матеріалів, сприяючи сталому розвитку промисловості через міждисциплінарну співпрацю.

***Ключові слова**: тверді сплави, цементовані карбіди, карбід вольфраму, переробка, циркулярна економіка, гідрометалургія, електрохімічне вилучення, адитивне виробництво, аналіз життєвого циклу, сталий розвиток, критичні матеріали, промислові стандарти*

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ОСОБЛИВОСТІ ВИМІРЮВАННЯ ЕЛЕКТРИЧНОГО ОПОРУ ВІЛЬНОСПЕЧЕНИХ КОМПОЗИТІВ AlN–50% SiC

Досліджено електричний опір вільноспечених керамічних композитів AlN–50% SiC, придатних для використання у якості об’ємних поглиначів мікрохвильового випромінювання. Об’ємний і поверхневий електричний опір композитів виміряли цифровим мультиметром UT 30D та цифровим мегаометром ВМ 500А. З цією метою розроблена двозондова методика вимірювання поверхневого опору малих за розміром зразків ~4,2×1,0 мм з композита. Виготовлено комплект пристроїв для нанесення чотирьох пар контактних площадок ~0,6 мм на поверхню диска та його надійного закріплення під час вимірювання поверхневого електричного опору.

Для трьох груп дисків з різною добротністю Q = 44, 55 та 70 визначені середні значення поверхневого опору складають: 136, 212 та 300 кОм, а відповідні їм середні значення об’ємного опору становлять: 7,0; 9,2 та 11,8 кОм. Аналіз масиву експериментальних даних виявив взаємозв’язок між поверхневим та об’ємним електричним опором: більшому об’ємному опору відповідає більший поверхневий опір, причому поверхневий опір більший ніж об’ємний у 19,4–25,4 рази.

Ключові слова: *поверхневий та об’ємний електричний опір, нітрид алюмінію, карбід кремнію, об’ємний поглинач мікрохвильового випромінювання, добротність, методика вимірювання поверхневого електричного опору, пристрої для вимірювання електричного опору.*

Вступ

Об’ємні поглиначі мікрохвильового випромінювання в електровакуумних приладах НВЧ-техніки конструктивно містяться у тій частині приладу, де близько протікає електронний потік. Струмопроходження потоку у робочому режимі практично завжди менше 100 %, отже електрони з пучка, рухаючись від катоду до колектора приладу, осідають на сповільнювальній системі (СпС), а деякі попадають на поверхню об’ємного поглинача. Тому бажано, щоб на постійному струмі матеріал поглинача мав достатню провідність. Це потрібно для того, щоб на його поверхні не відбувалося накопичення статичного заряду. Тоді навіть помірна