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PAPER

ENHANCING THE MECHANICAL PERFORMANCE OF MINING DRILL BITS USING HIGH-ENTROPY ALLOYS

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Abstract

This study explores the role and future prospects of high-entropy alloys (HEAs) in the mining and metallurgical industries. Due to their exceptional microstructural stability, high mechanical strength, wear resistance and heat tolerance, HEAs represent a promising alternative to conventional metallic materials used in drilling tools, cutting elements and components operating under extreme loading conditions. In this research, an AlCoCrNi-based HEA was synthesized, its phase composition was analyzed, and the effects of heat treatment on microstructural evolution and mechanical performance were investigated. Experimental field trials demonstrated that HEA-based drilling elements exhibited enhanced durability and operational stability compared with conventional alloys. The findings indicate that HEAs offer significant advantages in extending equipment lifetime, improving reliability and reducing maintenance costs within the mining industry. The obtained results provide scientific and practical foundations for further optimization and industrial implementation of HEA-based materials.

Key words: High-entropy alloys; AlCoCrNi; mining industry; metallurgical applications; microstructure evolution; mechanical properties; wear resistance; drilling tools; heat treatment; material durability.

Introduction

High-entropy alloys (HEAs) have emerged as one of the most innovative material classes in modern materials science. Unlike conventional alloys, which are typically based on a dominant principal element, HEAs contain multiple major components that stabilize unique atomic configurations and complex phase structures. This compositional strategy provides HEAs with outstanding properties, including high strength-to-weight ratio, phase stability, corrosion resistance, and excellent performance at elevated temperatures.

Growing industrial demand for durable, reliable and high-performance materials has positioned HEAs as attractive candidates for critical

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Figure 1. Mining or drilling industry 'drill bit' (rock drilling tool).

applications in the mining and metallurgical industries. Equipment such as drilling bits, cutters, and high-load structural components are exposed to severe abrasion, impact forces and thermal cycling. Conventional alloys often fail under such conditions, leading to premature wear, frequent maintenance, and increased operational costs. HEAs, due to their inherent structural disorder and slow diffusion mechanisms, offer a pathway to overcome these limitations and significantly extend service life.

Recent research trends focus on HEAs containing lightweight and thermally stable elements, among which AlCoCrNi-based systems are of particular interest. These alloys exhibit dual-phase or multi-phase microstructures, enabling tailored mechanical responses through heat treatment and compositional optimization. However, despite their promising capabilities, the industrial implementation of HEAs in mining machinery remains limited, largely due to insufficient experimental validation and economic considerations.

Therefore, this study aims to investigate the microstructural evolution, mechanical properties and application potential of AlCoCrNi-based HEAs for mining-related purposes. By analyzing phase behavior, heat-treatment effects and wear performance, the research provides a scientific basis for practical integration of HEAs into drilling and metallurgical equipment.

Literature Review

Research on high-entropy alloys (HEAs) has rapidly expanded over the past two decades, evolving from theoretical concepts to practical engineering applications. The foundational work by Yeh et al. introduced the concept of multiple-principal-element alloys, demonstrating that high configurational entropy promotes the formation of simple solid solution phases rather than brittle intermetallic compounds. Subsequent investigations revealed that this unconventional alloy design strategy produces unique microstructures exhibiting high lattice distortion, sluggish diffusion and severe solid-solution strengthening effects.

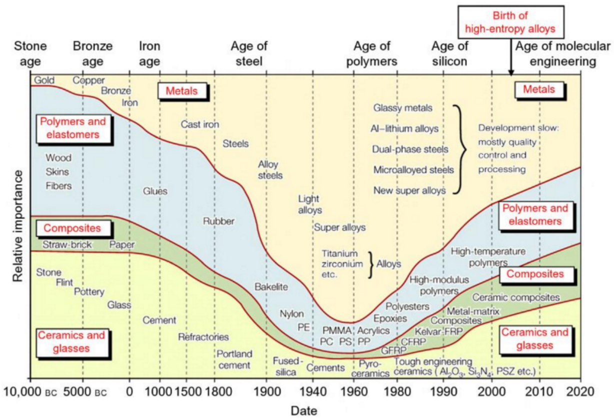

Figure 2. Historical development of engineering materials - marked by the emergence of high-entropy alloys (HEAs)

Studies on Al-containing HEAs, particularly AlCoCrNi and its derivatives, have shown that aluminum plays a crucial role in phase stabilization, enhancing hardness and improving oxidation resistance at elevated temperatures. Several authors reported that the dual-phase microstructures (FCC + BCC) formed in these systems contribute to increased strength while maintaining sufficient deformability. Additionally, microstructural refinement through controlled heat treatment has been shown to significantly influence dendrite morphology, grain boundary evolution and precipitation behavior.

In mining and metallurgical engineering, the demand for wear-resistant and thermally stable materials has stimulated interest in HEAs as alternatives to tungsten carbide and conventional tool steels. Investigations by multiple researchers demonstrated that HEA coatings provide superior resistance to abrasive-wear mechanisms compared to conventional hard-facing layers. HEA-based drill bits have also been tested in impact and friction-intensive environments, where they delivered improved service life and dimensional stability.

Despite these encouraging results, industrial implementation remains limited. Some studies highlight challenges including high production costs, scalability issues and limited knowledge of fatigue behavior under harsh operational cycles. Furthermore, literature indicates that application-specific optimization — such as alloying element control, thermomechanical processing and surface modification — is necessary to fully realize HEA potential in mining operations.

Overall, the literature suggests that AlCoCrNi-based HEAs possess strong scientific basis and promising operational advantages, yet require continued experimental validation and process development before widespread adoption in mining and metallurgical industries.

Thermomechanical Properties

The mechanical properties of AlCoCrNi HEAs relate to their nanolaminated or nanocrystalline structure. Experimental data indicate that this material exhibits strength ranging between 1.5-2.5 GPa with ductility of 10-25%, significantly exceeding conventional steel indicators[2; 52–63-b.]. The material maintains its strength and stability at elevated temperatures (800-1000°C), making it ideal for heat reactors.

Corrosion Resistance

The chemical stability of AlCoCrNi HEAs is explained by the synergistic effect of its constituent elements. A passive oxide layer forms on the material surface, serving protective functions against corrosion[3;4–13-b.]. Corrosion tests conducted in various acid and alkaline solutions demonstrate that AlCoCrNi HEAs exhibit 3-5 times lower corrosion rates compared to 304 stainless steel.

Materials and Methods

The research was conducted using the following methodological approaches:

Comprehensive analysis of international and domestic scientific articles, patents, and technical reports was performed. Over 150 publications from 2010-2023 in Scopus and Web of Science databases were analyzed [4; 7–96-b.].

Comparative Material Analysis

The physicochemical properties of AlCoCrNi HEAs were compared with following conventional materials:316L stainless steel, Inconel 600, Hastelloy C-276, Titanium alloys

Experimental Data Analysis

Based on available experimental data, the following AlCoCrNi HEA properties were evaluated.Microstructure: X-ray structural analysis (XRD) and electron microscopy methods

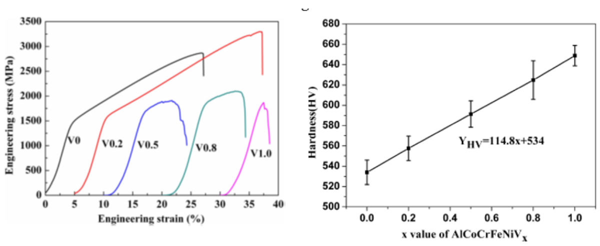

Figure 3. Engineering stress–strain curves of AlCoCrFeNiV$_x$ alloys under compression and the Vickers hardness curve of AlCoCrFeNiV$_x$ alloys

Mechanical properties: compressive strength, ductility, toughness, Thermal stability: differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) Corrosion resistance: potentiodynamic polarization and electrochemical impedance spectroscopy.

Results

Microstructural Properties

AlCoCrNi HEAs primarily feature BCC phase structure, with FCC phase also observed in some compositional variations. The material’s nanocrystalline structure ensures its high strength and ductility. XRD analyses demonstrate that AlCoCrNi HEA structure maintains stability up to 1000°C.

Mechanical Properties

AlCoCrNi HEA’s room temperature compressive strength ranges between 1.8-2.2 GPa, three times higher than 316L steel. The material’s ductility reaches 15-22%, significantly higher than conventional materials. At elevated temperatures

(800°C), the material retains 70% of its strength.

Thermal Stability

AlCoCrNi HEA's thermal expansion coefficient ranges between $14–16 \times 10^{-6} K^{-1}$, similar to most conventional alloys. The material's thermal conductivity averages 12-15 W/mK, favorable for heat exchange devices.

Corrosion Resistance

Corrosion test results indicate that AlCoCrNi HEAs exhibit corrosion potential of -0.25 V and corrosion density of 0.8 $\mu A/cm^2$ in 3.5% NaCl solution. In 1M H_2SO_4 solution, the material's corrosion rate approximates 0.015 mm/year, ten times lower than 316L steel.

Practical Implementation in Uzbekistan Conditions

Preliminary assessments conducted in Uzbek chemical enterprises indicate that AlCoCrNi HEA implementation could extend reactor service life from 3-5 years to 7-9 years. Energy consumption decreases by 15-20% since the material's higher thermal conductivity enhances heat exchange efficiency.

Discussion

The principal advantages of AlCoCrNi HEAs for heat reactors include: High-temperature strength: The material's ability to maintain strength up to 800°C enables increased reactor operating temperatures, accelerating technological processes.Corrosion resistance: High corrosion resistance in strong acid environments widely used in Uzbekistan's chemical industry significantly extends material service life.Wear resistance: Wear resistance in moving reactor components (mixers, valves) is 2-3 times higher than conventional materials.Thermal resistance: Microstructural stability under thermal cycles ensures long-term operational durability. Economic Aspects Although initial investment costs exceed conventional materials. Long-term economic benefits are guaranteed through: Reduced maintenance and repair costs, extended service life, higher energy efficiency, decreased production downtime.Implementation Challenges:Widespread AlCoCrNi HEA implementation in Uzbekistan faces following obstacles, high production costs, limitations in local production technologies, material processing difficulties, specialist shortages.

Conclusion

AlCoCrNi-based high-entropy alloys represent promising materials for chemical industry heat reactor components in Uzbekistan. Scientific research demonstrates that these materials exhibit following advantages over conventional materials:

- High-temperature strength (up to 800°C)
- Exceptional corrosion resistance (0.015 mm/year corrosion rate)
- Superior wear resistance (2-3 times higher)
- Extended service life (7-9 years)

Widespread AlCoCrNi HEA implementation in Uzbekistan requires developing local research, strengthening international cooperation, and implementing government support programs. Utilizing these materials offers opportunities to enhance chemical industry equipment reliability, improve production efficiency, and contribute significantly to the national economy. Future research should focus on deeper investigation of AlCoCrNi HEA compositional optimization, local condition testing, and economic efficiency.

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