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The Progress in the Coupling and Optimization of Mechanical and Corrosion Properties in High-Entropy Alloys

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Abstract. High-Entropy Alloys (HEAs), as emerging multi-component materials, exhibit great potential for functional applications, particularly in corrosion-resistant coatings due to their outstanding mechanical performance and excellent corrosion resistance. However, achieving an effective balance between mechanical performance and corrosion resistance remains a key challenge for practical implementation. This study aims to elucidate the intrinsic relationship between mechanical performance and corrosion behavior in HEAs, while summarizing recent advances and emerging trends in the field. Through a review of recent literature, this paper summarizes the mechanical advantages of HEAs over conventional alloys in terms of strength, ductility, fracture toughness, fatigue endurance, and crack resistance. In addition, it examines their corrosion characteristics, particularly under chloride-containing environments. The results demonstrate that HEAs possess unique potential for achieving a synergistic optimization of mechanical and corrosion performance, although challenges such as compositional complexity and unclear service mechanisms persist. As such, it outlines the major bottlenecks and future research directions, offering theoretical insights and practical implications for the design and application of HEAs.

Keywords: High-Entropy Alloy (HEA), Mechanical Property, Corrosion Property, Corrosion-Mechanical Trade-Off

1. Introduction

The development of advanced materials that combine high mechanical performance with exceptional corrosion resistance is a major challenge in key engineering sectors, particularly aerospace, automotive, and marine industries [1]. Traditional materials, such as steels and nickel-based superalloys, often face inherent trade-offs between strength and ductility or corrosion resistance, limiting their effectiveness in harsh environments. High-entropy alloys (HEAs), composed of multiple principal elements in near-equal atomic proportions, have emerged as a promising solution, offering high strength, excellent wear resistance, and enhanced corrosion properties, making them ideal candidates for extreme conditions where conventional alloys typically fail. HEAs exhibit remarkable mechanical properties like superior strength-ductility synergy, high fracture toughness, and exceptional fatigue and creep resistance at elevated temperatures. These properties stem from several intrinsic mechanisms, such as solid-solution strengthening, lattice distortion, and precipitation hardening, which provide a competitive edge over traditional alloys.

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Moreover, the diverse compositions and phase structures in HEAs enable tailoring to specific performance requirements. However, the ability to achieve both high mechanical performance and outstanding corrosion resistance in HEAs remains an ongoing challenge [2]. Despite the promising potential of HEAs, the complexity of their compositions and microstructures introduces trade-offs that need to be carefully balanced. And the fundamental mechanisms that govern the interactions between mechanical integrity and corrosion resistance are not yet fully understood, presenting significant challenges for optimizing these alloys for real-world applications. This paper aims to review the recent advancements in the development of HEAs, focusing on their mechanical properties and corrosion behavior. It also explores strategies for overcoming the challenges of balancing these properties, such as compositional optimization, microstructural design, and surface modification. Besides, it discusses explores future HEA research directions, emphasizing advanced characterization and computational tools to accelerate the discovery and design of high-performance multifunctional alloys.

2. Mechanical properties of high-entropy alloys

2.1. Strength-ductility relationship and underlying mechanisms

To meet the demanding requirements of aerospace, automotive, and defense sectors, material scientists have long sought ways to overcome the inherent trade-off between strength and ductility. In response to the limitations of conventional alloys, which often require a trade-off between strength and ductility, high-entropy alloys such as the $Fe_{50}Mn_{30-x}Co_{10}Cr_{10}Cu_x$ have emerged as promising candidates that overcome this constraint. For instance, the $Fe_{50}Mn_{30-x}Co_{10}Cr_{10}Cu_x$ alloy demonstrates a yield strength exceeding 700 MPa along with an elongation greater than 30%, significantly surpassing conventional high-strength steels and duplex stainless steels, which generally offer comparable strength but much lower ductility[3,4]. This superior performance is attributed to several intrinsic mechanisms, among which solid-solution strengthening and significant lattice distortion, caused by atomic-scale chemical disorder, play a key role by effectively hindering dislocation motion. Precipitation hardening also plays a crucial role in certain high-entropy alloy systems. For instance, in a Ni–Fe–Cr–Co–Al alloy, nanoscale precipitate formation leads to exceptional strength-ductility synergy, achieving compressive strengths up to 950 MPa while maintaining considerable ductility [5]. This improvement arises from the incorporation of both ductile matrix and hard precipitate phases, enabling dual-phase HEAs to exploit multiple intrinsic strengthening mechanisms simultaneously.This has positioned HEAs as a promising class of structural materials, with future gains anticipated through continued exploration of composition-structure correlations.

2.2. Fracture toughness and crack propagation resistance

Fracture toughness is a critical property for structural materials operating in demanding environments, as it governs the material's resistance to crack initiation and propagation. In contrast to strength or ductility alone, toughness reflects a material's ability to absorb energy before failure, hence making it a crucial parameter for ensuring safety and reliability in demanding applications such as aerospace and marine engineering. In HEAs, crystal structure plays a key role in fracture behavior. FCC-structured HEAs typically exhibit higher toughness due to their superior plasticity. For example, the equiatomic Cantor alloy, with an FCC structure, shows fracture toughness values around 200 MPa√m, higher than many stainless steels (100~150 MPa√m), and retains this toughness

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even at cryogenic temperatures [6]. In contrast, BCC-structured HEAs, such as TiZrHfNbTa, offer higher strength but tend to be more brittle due to limited plasticity, especially at low temperatures [7]. To achieve balanced properties, recent studies focus on dual-phase HEAs that combine FCC and BCC structures. By tailoring composition, such as through the addition of aluminum or silicon, certain FeCrNi-based HEAs can develop heterogeneous FCC+BCC phase structures, resulting in a yield strength of approximately 470 MPa, an ultimate tensile strength of 930 MPa, and an elongation of 30% [8,9]. Fracture toughness in HEAs can be effectively tuned via compositional and microstructural design. Continued investigation into fracture mechanisms is key to developing alloys with optimized strength–toughness balance.

2.3. Fatigue and creep resistance at elevated temperatures

In high-temperature environments, such as those found in turbine blades, power generation systems, and aerospace propulsion, materials are subjected to cyclic loading and sustained stress over extended periods. Under such extreme conditions, robust resistance to both fatigue and creep is imperative to preserve structural integrity and ensure long-term operational safety. As nickel-based superalloys near their performance limits in high-temperature environments, HEAs are increasingly recognized as viable alternatives. FCC-structured HEAs, such as $Al_{0.3}$CoCrFeNi, exhibit excellent fatigue resistance under cyclic loading. This alloy maintains a stable dislocation structure and shows negligible cyclic softening even after 10^7 cycles, highlighting its durability under mechanical fatigue. Its retained FCC phase and fine microstructure contribute to delaying microcrack initiation and propagation [10]. For creep resistance, refractory HEAs, particularly those composed of Mo, Nb, Ta, and Wk demonstrate outstanding stability under long-term loading at temperatures approaching 1200 °C. The exceptional creep resistance and thermal stability of MoNbTaWHfN are enabled by its BCC crystal structure, incorporation of high-melting-point elements, and inherently sluggish diffusion kinetics, making it superior to Ni-based counterparts [11]. The high-temperature performance of HEAs is governed by a combination of compositional, structural, and processing factors. To improve high-temperature performance, refractory elements are used to enhance thermal stability, while carefully balanced Al additions strengthen oxidation resistance without impairing phase integrity. The phase structure plays a vital role, FCC HEAs exhibit superior fatigue resistance owing to their ductility, while BCC or B2 phases offer higher strength and creep resistance, though they may suffer from brittleness without proper microstructural tuning. Grain characteristics are equally important: fine grains delay crack initiation and improve fatigue life, while coarse grains with stable boundaries boost creep resistance. Additive manufacturing enables microstructural control that enhances fatigue resistance and limits creep via tailored solidification, grain structure, and composition.

3. Corrosion characteristics of high-entropy alloys

3.1. General corrosion in chloride-containing aqueous environment

Marine and industrial environments impose severe demands on structural materials owing to chloride-induced corrosion. In such corrosive environments, HEAs frequently outperform conventional stainless steels in terms of corrosion resistance. For example, the equiatomic CoCrFeNiMn alloy exhibits greatly lower passive current density and reduced pitting susceptibility compared to 304 stainless steel in 3.5% NaCl solution. This indicates the formation of a more stable and protective passive film. The excellent corrosion resistance of HEAs is largely attributed to the

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presence of Cr and Mo. Chromium promotes the formation of a dense Cr_2O_3-rich passive layer that inhibits ion penetration, while molybdenum enhances pitting resistance and contributes to film self-repair. The multi-elemental nature of HEAs also improves chemical homogeneity and reduces selective dissolution, further stabilizing the passive film. These characteristics make HEAs particularly suited for chloride-rich environments, where traditional materials often suffer from localized corrosion.

3.2. High-temperature oxidation behavior

In high-temperature applications such as turbines and aerospace components, oxidation resistance is essential to ensure long-term material stability. HEAs, especially those containing aluminum (Al), have demonstrated superior oxidation resistance due to their ability to form dense, protective Al_2O_3 (alumina) layers. For example, AlCoCrFeNi forms a continuous Al_2O_3 scale at 900 °C, reducing oxidation-induced mass gain by up to 70% compared to conventional Ni-based superalloys, which typically form less stable mixed oxides [12]. This highlights HEAs' advantage in reducing material loss and improving oxidation stability. The effectiveness of the oxide layer strongly depends on alloy composition. Al plays a dominant role in promoting stable alumina formation, while titanium (Ti), in moderate amounts, can enhance scale adherence. However, a proper Al-Ti balance is critical; excessive Ti may lead to volatile TiO_2 formation, undermining oxidation resistance. Optimizing the Al/Ti ratio promotes a stable oxide layer and limits degradation. Thus, Al-containing HEAs surpass conventional alloys in high-temperature oxidation resistance, mass stability, and thermal durability.

3.3. Localized and environment-assisted corrosion

Localized corrosion, such as galvanic corrosion and stress-corrosion cracking (SCC), presents a critical threat to structural materials due to its sudden onset and unpredictable failure. Despite their generally good corrosion resistance, HEAs remain vulnerable to localized degradation. In AlCoCrCuFeNi, Cu-rich phase segregation can promote micro-galvanic cell formation, accelerating localized corrosion in chloride-rich environments [13]. Similarly, FCC-structured HEAs like CoCrFeNiMn can be prone to SCC in chloride-rich environments, primarily due to hydrogen embrittlement under tensile stress and localized passive film breakdown [14]. The tendency for localized corrosion in HEAs is influenced by factors such as elemental segregation, phase inhomogeneity, residual stress, and passive film stability. Although the multicomponent design of HEAs improves general corrosion resistance, it also introduces chemical and structural complexities that may promote localized attack under aggressive environments. Effective mitigation requires deeper insight into the microstructural drivers of localized corrosion and their interplay with environmental conditions. Future research should focus on alloy design strategies that reduce segregation and inhomogeneity, coupled with in-situ monitoring and predictive modeling to better understand and mitigate localized corrosion.

4. Interrelationship between mechanical integrity and corrosion resistance

4.1. Shared influencing factors on dual performance

In many engineering scenarios, such as marine, aerospace, and chemical environments, materials must combine high strength with corrosion resistance. Balancing strength and corrosion resistance in HEAs relies on composition, grain structure, and phase distribution. Elements like Chromium (Cr)

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offer dual benefits by forming protective films and enhancing solid-solution strengthening. However, excessive Cr (>20 at.%) can destabilize the matrix and lead to brittle intermetallic phases. Al improves oxidation resistance and stabilizes BCC phases for strength, but may reduce aqueous corrosion resistance due to passive film instability, especially in chloride environments. For example, AlCoCrFeNi exhibits better oxidation resistance but reduced pitting resistance than Al-free CoCrFeNiMn in NaCl solution [15]. Grain refinement enhances strength via the Hall-Petch effect but increases grain boundary area, which can serve as corrosion initiation sites. A study on nanocrystalline CoCrFeMnNi showed about 30% higher yield strength compared to its coarse-grained counterpart, but also revealed increased susceptibility to intergranular corrosion in the absence of effective grain boundary passivation. This highlights structural trade-offs in HEAs, where grain size and phase structure govern performance. Single-phase FCC alloys typically provide consistent strength and improved corrosion resistance. In contrast, secondary phases such as Laves or intermetallics enhance strength via precipitation hardening but may form galvanic couples that promote localized corrosion. For instance, Al-rich HEAs with fine precipitates exhibit higher hardness around 500 HV, but suffer from pitting at intermetallic interfaces in chloride environments. Therefore, dual performance requires balancing strengthening with passivation, grain refinement with corrosion resistance, and hard phases with structural uniformity.

4.2. Trade-offs and performance conflicts

Though HEAs offer the potential for both strong mechanical and corrosion properties, optimizing both simultaneously often involves trade-offs. Enhancing one property may negatively impact the other due to competing effects in composition and microstructure. For instance, elements like Al and Ti improve strength by promoting BCC phase formation and precipitation hardening, enhancing yield strength and creep resistance. However, their high oxidation affinity can lead to oxide scale spallation under thermal cycling, compromising long-term oxidation protection. It is found that elements like molybdenum (Mo), niobium (Nb), and copper (Cu) offer functional benefits like improved corrosion resistance, strength, or conductivity, but also introduce trade-offs by boosting grain boundary segregation, brittle intermetallics, or micro-galvanic corrosion [16,17]. A trade-off exists between ductility and SCC resistance, as FCC HEAs like CoCrFeNiMn, though ductile and tough, are prone to hydrogen ingress due to their open crystal structure under stress. This heightens their vulnerability to hydrogen embrittlement and SCC, especially in chloride-rich environments where dissolution and hydrogen effects interact. These cases highlight the trade-off between mechanical and corrosion properties, necessitating strategies like dual-phase structures, composition gradients, or surface treatments for balanced HEA performance.

4.3. Integrated optimization strategies for multifunctional performance

With growing demands in aerospace, marine, and energy sectors, HEAs must move beyond isolated properties to offer integrated performance under complex service conditions. This necessitates a shift from traditional single-property optimization toward integrated material design, where mechanical and corrosion properties are synergistically tailored through coordinated strategies. Three key pathways for achieving multifunctional performance in HEAs are compositional design, surface engineering, and thermomechanical processing. The efficient discovery of HEAs with balanced strength and corrosion resistance is made possible via the integration of machine learning and high-throughput computational screening. For example, elements like Cr and Mo improve passivation and pitting resistance, while Co and Ni enhance toughness and phase stability. Careful

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compositional tuning helps minimize trade-offs and boost overall performance [18]. Surface modification techniques like laser cladding, plasma nitriding, and PVD coatings enable targeted reinforcement where wear and corrosion begin, forming protective layers without compromising bulk mechanical integrity. In environments with combined mechanical and corrosive stress, surface treatments play a key role. Techniques based on severe plastic deformation, including high-pressure torsion, equal channel angular pressing, and accumulative roll bonding, refine grain structures to strengthen the material while simultaneously mitigating elemental segregation that can trigger localized corrosion or destabilize phases. Properly controlled SPD processes enhance both mechanical integrity and corrosion uniformity, making them essential in HEA processing. Integrating these methods enables the design of tailored microstructures and compositions to meet the demanding requirements of future engineering applications. Ongoing advances in computational-experimental frameworks will further accelerate this integrated development.

5. Emerging directions and future perspectives

High-entropy HEAs mark a breakthrough in alloy design, uniting exceptional mechanical performance with enhanced corrosion resistance. To advance toward real-world applications, future research must tackle challenges of scalability, cost, and environmental adaptability. Building on current progress, emerging directions now offer a roadmap for the next phase of HEA development.

A key direction involves enhancing in-situ characterization capabilities to capture real-time material responses during simultaneous mechanical loading and environmental exposure. Techniques such as transmission electron microscopy and synchrotron-based X-ray diffraction are increasingly used to track dislocation movement, phase changes, crack growth, and passive film behavior. Such real-time insights are essential for understanding how mechanical stress and corrosion interact to influence long-term material reliability. Concurrently, there is a growing strategic focus on engineering low-cost, resource-efficient HEAs to enable broader industrial scalability and sustainability. Conventional HEAs often rely on costly or scarce elements like cobalt, nickel, and molybdenum, which limit scalability. As such, research is shifting towards Fe-, Mn-, Al-, and Cr-based systems. However, these alternatives often struggle with challenges in phase stability, corrosion resistance, or mechanical performance. Meeting these challenges requires precise compositional tuning, supported by approaches such as microalloying, dual-phase structuring, and computational optimization to balance cost and functionality.

Another expanding frontier is the use of HEAs in extreme environments, such as nuclear reactors, where their sluggish diffusion and high radiation tolerance help mitigate swelling and embrittlement that often compromise conventional materials. Besides, certain HEA compositions are being explored for high-temperature structural roles and as electrocatalysts in corrosive chemical environments, underscoring their versatility and the need for targeted, application-specific design. By leveraging machine learning with high-throughput experimental data, researchers are transforming HEA discovery, shifting from traditional trial-and-error approaches to predictive modeling that accelerates composition selection, property optimization, and process refinement. As materials databases grow and algorithm precision advances, AI will play an increasingly pivotal role in navigating the complex compositional landscape of HEAs. These developments signal a shift in HEA research towards a deeper mechanistic understanding, greater functional versatility, and improved economic viability. Continued progress in these areas is crucial for unlocking the full potential of HEAs in future high-performance, sustainable engineering applications.

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6. Conclusion

This paper has reviewed recent advancements in understanding and optimizing the interplay between mechanical properties and corrosion resistance in HEAs. It highlights that while some HEAs exhibit exceptional mechanical strength or corrosion resistance individually, achieving a favorable balance between the two remains challenging. Key findings include: alloying elements and phase composition influence both mechanical and corrosion properties, often in opposing ways. Tailoring microstructures, controlling phase distributions, and optimizing processing techniques help align these properties, while advanced surface modification and computational design methods offer effective solutions to mitigate trade-offs. Despite these advancements, this review acknowledges several limitations in the current research landscape. Many studies evaluate mechanical and corrosion properties independently, making it difficult to draw consistent conclusions on their interdependence. Moreover, experimental data are often confined to specific environments, thus complicating comparisons across studies. The underlying mechanisms driving the synergy or conflict between strength and corrosion resistance are still not fully understood. Future research should prioritize developing standardized evaluation systems that assess both properties under comparable conditions. Emphasizing in-situ or operando techniques may uncover dynamic mechanisms during corrosion or mechanical deformation. Furthermore, integrating high-throughput experiments with machine learning could accelerate the discovery of HEAs with optimal performance combinations.

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