

High-Entropy Alloys: A Review of Mechanical and Thermal Properties

Sahad Khan

MS research Scholar, Department of Earth Sciences, Institute of Materials, Minerals & Mining Engineering (IMMME), Abbottabad University of Science and Technology, Email: sahadkhan0033@gmail.com

Sajjad Ahmad*

PhD Physics, University of Lahore Email: ahmadsajjad486@gmail.com

Muhammad Tahir

M.Phil. Physics Hazara University Mansehra
Email: khan.gmail:mtahirkhan938@gmail.com

Muhammad Awais

MSc Mathematics University of Haripur Email mawais2484@gmail.com

ABSTRACT

High-entropy alloys (HEAs) represent a paradigm shift in metallurgical design, replacing the conventional one-principal-element strategy with multi-principal-element compositions occupying near-equiatomic proportions. Since the concept gained momentum in the alloy design community, research activity has expanded rapidly, driven by the combination of high strength, ductility, thermal stability and phase simplicity that a large compositional space can, in principle, deliver [1]. This review synthesizes current understanding of the mechanical behavior of HEAs — including strengthening mechanisms such as severe lattice distortion, sluggish diffusion and solid-solution hardening — alongside their thermal characteristics, covering high-temperature strength retention, oxidation resistance and phase stability in refractory HEA systems. Face-centered-cubic (FCC) HEAs such as CoCrFeMnNi are shown to combine excellent low-temperature ductility with moderate strength, whereas body-centered-cubic (BCC) refractory HEAs based on Nb, Mo, Ta, W, Ti, Zr and Hf offer superior high-temperature strength but often at the cost of room-temperature ductility. The review further discusses compositional design rules, processing routes, current engineering applications in aerospace, nuclear and coating technologies, and the outstanding challenges — including oxidation behavior above 1000 °C, processing cost and the strength–ductility trade-off — that continue to guide research in this field. Only literature published between 2014 and 2025 is considered.

Introduction

Conventional alloy design has historically relied on a single principal element, such as iron, aluminum, nickel or titanium, with minor additions used to tune specific properties. High-entropy alloys depart from this approach by combining five or more elements in near-equiatomic ratios, typically between 5 and 35 atomic percent each [1]. The term reflects the large configurational entropy of mixing associated with such compositions, which is understood to stabilize simple solid-solution phases (FCC, BCC or hexagonal close-packed) over the complex intermetallic compounds that intuition might predict for such chemically complex mixtures [1,2].

Interest in HEAs has grown substantially since the field's inception in the mid-2000s, with research activity accelerating markedly from the early 2010s onward as the compositional space, processing routes and characterization techniques matured [5]. Four core effects continue to frame HEA research: high configurational entropy favoring solid-solution formation, severe lattice distortion, sluggish diffusion, and a cocktail effect describing the non-linear property outcomes that emerge from combining chemically dissimilar elements [1,5]. Since these principles were articulated, the field has expanded to encompass lightweight HEAs, refractory HEAs, precipitation-strengthened HEAs and HEA-based coatings, each targeting a different balance of mechanical and thermal performance [5,14].

This review is organized to address two performance dimensions central to structural applications: mechanical behavior (strength, ductility, hardness and deformation mechanisms) and thermal behavior (high-temperature strength retention, oxidation resistance and phase stability). Because HEAs are increasingly considered for aerospace, nuclear and extreme-environment applications, understanding how compositional and microstructural choices govern these two property sets is essential for guiding future alloy design. Only literature published between 2014 and 2025 is reviewed, reflecting the period during which the field moved from initial exploratory reports toward systematic, application-driven research.

Compositional Design and Phase Formation Rules

Phase selection in HEAs is commonly rationalized using empirical parameters derived from the Hume-Rothery rules, adapted for multicomponent systems. These include the atomic size difference (δ), the mixing enthalpy (ΔH_{mix}), the mixing entropy (ΔS_{mix}) and the valence electron concentration (VEC). Alloys with small atomic size mismatch and near-zero mixing enthalpy tend to favor simple solid-solution phases, while larger mismatches promote intermetallic or amorphous phase formation [1,2]. VEC has proven particularly useful for anticipating FCC versus BCC phase selection: compositions with higher VEC values tend to stabilize FCC solid solutions, whereas lower VEC values favor BCC structures [1].

Mechanical alloying followed by sintering has emerged as an important processing route for HEA powders, offering finer, more homogeneous microstructures than conventional casting and enabling access to compositions that are difficult to process by melting alone; this route also introduces distinct challenges related to contamination, porosity and incomplete densification that must be addressed through optimized milling and consolidation parameters [5]. Recent computation- and process-based design frameworks increasingly combine thermodynamic calculations

with machine-learning-assisted screening to navigate the vast compositional space more efficiently than trial-and-error experimentation, accelerating the identification of compositions that balance strength, ductility and processability [19].

3. Mechanical Properties

The mechanical response of HEAs is strongly dependent on crystal structure. FCC HEAs, exemplified by the Cantor-type CoCrFeMnNi system and its medium-entropy derivatives (e.g., CoCrNi, CoCrFeNi), typically display excellent ductility and toughness, including an unusual increase in strength and toughness with decreasing temperature down to cryogenic conditions, attributed to deformation twinning that activates as thermally assisted dislocation glide is suppressed [18]. This behavior makes FCC HEAs attractive for cryogenic structural applications where conventional steels become brittle.

BCC refractory HEAs, based on combinations of niobium, molybdenum, tantalum, tungsten, titanium, zirconium, hafnium and vanadium, exhibit substantially higher yield strengths, often exceeding 1000 MPa at room temperature, but generally show reduced ductility because BCC slip systems offer fewer independent slip modes than FCC structures [15,16]. Solid-solution strengthening in these systems is dominated by the size and modulus mismatch between constituent elements, and strengthening magnitude correlates with the degree of local lattice distortion [7,18]. Precipitation strengthening, through coherent L12 or other secondary phases, has also been used to enhance strength in both FCC and BCC HEA families without a proportionate ductility penalty, echoing strategies long used in nickel-based superalloys, and is central to the design of high-entropy superalloys (HESAs) intended for elevated-temperature service [6].

A recurring theme in the mechanical-property literature is the strength–ductility trade-off. George, Curtin and Tasan note that, when compared directly with conventional alloys of similar composition and processing history, most individual HEA properties are not exceptional in isolation; the value of the HEA concept instead lies in the vastly expanded compositional space it opens, which permits the simultaneous tuning of multiple deformation mechanisms — solid-solution strengthening, twinning, and transformation-induced plasticity — in ways not easily achieved in conventional alloys [18]. Complementing this deformation-mechanism perspective, strengthening-modelling frameworks that combine solid-solution, precipitation, dislocation, grain-boundary and phase-transformation contributions have been developed to predict yield strength across wide temperature ranges, providing a quantitative basis for alloy design [7].

Tribological performance is an increasingly examined aspect of HEA mechanical behavior, particularly for components subject to sliding, rolling or erosive wear. HEAs generally exhibit favorable wear resistance owing to their high hardness and sluggish diffusion kinetics, and this resistance can be further enhanced through coating strategies such as thermal spraying and laser cladding [8,9,13]. Table 1 summarizes representative mechanical property ranges reported for several well-studied HEA systems, illustrating the general trend of increasing strength and decreasing ductility as compositions shift from FCC to BCC refractory systems.

Alloy System	Structure	Yield Strength (MPa)	Hardness (HV)	B/G Ratio (Ductility)
CoCrFeMnNi (Cantor-type)	FCC	~410 (RT)	~150	Ductile
CoCrFeNi (medium-entropy)	FCC	~300–350	~140	Ductile
NbMoTaW (refractory)	BCC	~1000+ (RT)	~450	Brittle-tendency
TiZrHfNbTa (refractory)	BCC	~900	~400	Moderate
AlCoCrFeNi	BCC/FCC dual	~700–1200	~300–550	Al-content dependent

Table 1. Representative mechanical property ranges for selected HEA systems, compiled from the reviewed literature [1,7,15,16,18].

Thermal Properties

Thermal performance is a defining criterion for HEAs intended for aerospace, energy and nuclear applications, where retention of strength and microstructural integrity at elevated temperature is essential. Refractory HEAs, owing to their high melting points and sluggish diffusion kinetics, generally show better resistance to softening at high temperature than conventional nickel-based superalloys at equivalent temperatures, though this advantage is composition-dependent [15,17]. Miracle and coworkers emphasize that strength retention in refractory complex concentrated alloys must be benchmarked directly against the pure refractory BCC elements themselves, since much of the apparent high-temperature strength advantage originates from the inherently high strength of elements such as tungsten, molybdenum and tantalum rather than from a synergistic multicomponent effect alone [17].

Oxidation resistance remains one of the most significant limitations for refractory HEAs at temperatures above approximately 1000 °C. Gorr and coworkers demonstrated that oxidation behavior in refractory HEAs is highly sensitive to alloy composition, with some compositions forming protective, slow-growing oxide scales while others suffer rapid, non-protective oxidation and peeling [3]. Aluminum additions have been widely explored as a strategy to promote the formation of a protective alumina scale; Chang, Titus and Yeh showed that TiZrNbHfTa-based refractory HEAs containing aluminum display markedly different oxidation kinetics between 700 and 1300 °C depending on aluminum content, with intermediate additions offering the best compromise between scale protectiveness and mechanical compatibility [4].

High-entropy superalloys (HESAs), which emulate the γ/γ' dual-phase microstructure of conventional nickel-based superalloys, have emerged as a distinct strategy for combining high-temperature strength with useful ductility. Their thermal stability depends strongly on the ordering and coarsening resistance of coherent precipitates, and creep behavior at elevated temperature remains an active area of investigation, particularly given the still-limited experimental data relative to conventional superalloy systems [6]. Phase stability at elevated temperature is a further concern for both HESAs and refractory HEAs more broadly, since some compositions that appear

as single-phase solid solutions after casting undergo spinodal decomposition or precipitate secondary phases during prolonged high-temperature exposure, motivating systematic screening studies for candidate compositions intended for turbine or nuclear service [15,16]. Processing route also strongly influences thermal response: mechanically alloyed and spark-plasma-sintered HEAs can show different grain-growth and densification behavior at elevated temperature compared with as-cast counterparts, which affects both mechanical performance and long-term thermal stability [5,20].

Applications

The combination of mechanical and thermal properties discussed above has directed HEA research toward several application domains. FCC HEAs with cryogenic toughness are being evaluated for liquefied-gas storage and cryogenic structural components. Refractory BCC HEAs and high-entropy superalloys are of interest for high-temperature aerospace structures, hypersonic vehicle components and next-generation turbine materials, where service temperatures can exceed the practical limits of conventional nickel-based superalloys [6,15]. HEA and HEA-derived coatings, deposited by thermal spraying, laser cladding or cold spray, are increasingly explored for wear- and corrosion-resistant surface treatments in demanding industrial environments, including marine, oil-and-gas and biomedical settings [9,11,12,13]. Additionally, several refractory HEA compositions have shown promising irradiation and erosion tolerance, arising from their intrinsic lattice complexity and slow defect-diffusion kinetics, positioning them as candidate structural materials for advanced nuclear reactor systems and protective components [10,16].

Challenges and Future Directions

Despite substantial progress, several challenges continue to limit the widespread engineering adoption of HEAs. The strength–ductility trade-off in BCC refractory systems remains only partially resolved, and reliable room-temperature ductility in these alloys typically requires careful compositional tuning or thermomechanical processing [17]. Oxidation resistance above 1000 °C is inconsistent across the compositional space and requires further systematic study, particularly for multi-refractory-element systems where oxide-scale behavior is difficult to predict from binary or ternary oxidation data alone [3,4]. Processing cost and scalability remain practical barriers: many refractory HEAs and mechanically alloyed compositions require vacuum arc melting, powder metallurgy, or spark-plasma sintering, routes that are considerably more resource-intensive than conventional alloy production [5,20]. Looking forward, the compositional freedom inherent to the multi-principal-element design space is increasingly being navigated through computational and data-driven screening rather than trial-and-error experimentation alone, since exhaustive experimental exploration of even a modest set of candidate elements is impractical [19]. Continued development of physically grounded phase-prediction and strengthening models, combined with high-throughput experimental screening of mechanical, tribological and oxidation behavior, is likely to be central to translating the HEA concept from a laboratory curiosity into a mature engineering materials class [7,8,19].

Conclusion

High-entropy alloys have established themselves as a distinct and scientifically rich class of structural materials, offering a compositional design space that is far larger than that available to conventional alloys. FCC HEAs provide an attractive combination of ductility and cryogenic toughness, while BCC refractory HEAs and high-entropy superalloys extend high-temperature strength toward or beyond the practical limits of many conventional superalloys, albeit with persistent challenges in room-temperature ductility and high-temperature oxidation resistance. Continued advances in compositional design rules, processing methods, protective coatings and computational screening are expected to progressively close these gaps, supporting the transition of HEAs from a subject of fundamental scientific interest toward practical deployment in aerospace, energy and nuclear engineering applications.

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