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REVIEW ARTICLE

Advancing Material Frontiers with High Entropy Alloys: A Review of Structure, Properties, and Potential

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ABSTRACT:

High Entropy Alloys (HEAs) represent a revolutionary class of materials engineered for high- performance applications across aerospace, automotive, energy, and defense industries, where mechanical integrity, thermal stability, and corrosion resistance are critical. Unlike conventional alloys based on one or two principal elements, HEAs are composed of five or more principal elements in near-equimolar ratios, resulting in elevated configurational entropy and the stabilization of simple solid-solution phases. This unique compositional strategy leads to exceptional mechanical strength, wear resistance, and structural stability, even under extreme environmental conditions. The synergistic effects of high entropy, severe lattice distortion, sluggish diffusion, and the cocktail effect contribute to the remarkable physical and chemical properties observed in HEAs. This review explores the principles of alloy design, fabrication techniques, microstructural evolution, and mechanical performance of HEAs. It further highlights the broad potential of HEAs as next-generation structural materials and functional components, with particular emphasis on their adaptability through compositional tuning and advanced processing techniques. Continued research is essential for optimizing HEAs for mass production and application-specific performance.

KEYWORDS: High entropy alloys; Advanced materials; Structural applications; Mechanical properties; Solid-solution strengthening.

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1. INTRODUCTION

For over a century, alloy design followed a single-principal-element paradigm: iron, aluminium, nickel, or titanium formed the base of an alloy system, to which minor alloying additions were made to tailor specific properties. This paradigm was fundamentally challenged in 2004 when Yeh and co-workers reported nanostructured alloys containing five or more principal elements in near-equimolar proportions, coining the

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term "high entropy alloys" (HEAs) on the premise that high configurational entropy stabilises a simple solid-solution phase in preference to the complex intermetallic compounds that classical alloy theory would predict [1]. Independently, Cantor and co-workers reported a closely related equiatomic multicomponent alloy system in the same year, and the resulting CrMnFeCoNi "Cantor alloy" remains among the most extensively studied HEA compositions [2]. Ranganathan had anticipated the conceptual importance of such multi-element "cocktail" alloys slightly earlier, in a widely cited 2003 commentary [3].

HEAs are conventionally understood through four interrelated core effects: the high-entropy effect, which thermodynamically favours solid-solution phase formation; severe lattice distortion, arising from the differing atomic radii of the constituent elements; sluggish diffusion, which retards phase transformation and coarsening kinetics; and the cocktail effect, describing the synergistic combination of the properties of the constituent elements beyond simple rule-of-mixtures prediction [1,4,5]. Together, these effects give rise to combinations of strength, ductility, thermal stability, and corrosion and wear resistance that frequently exceed what would be expected from the alloy's elemental composition alone, motivating over two decades of sustained research interest across academic and industrial materials science [6].

This review compiles and synthesises the current understanding of HEA compositional design principles, the major fabrication and processing routes, the microstructural evolution that governs phase selection, and the mechanical, wear, and corrosion performance reported across the principal HEA families. It further surveys the emerging application landscape for HEAs, spanning structural aerospace and automotive components, high-temperature energy-sector hardware, protective coatings, and biomedical and energy-storage functional applications, and identifies the principal challenges that remain before HEAs can transition from laboratory-scale demonstration to industrial-scale, application-specific deployment.

2. COMPOSITIONAL DESIGN PRINCIPLES

2.1. Defining Criteria and Classification

HEAs are formally defined as containing five or more principal elements, each present between 5 and 35 atomic percent, with configurational entropy exceeding 1.5R (R being the gas constant) in the random solid-solution state; alloys with entropy between 1R and 1.5R are classed as medium-entropy alloys [7,8]. Within this framework, HEAs are broadly categorised into five compositional families: 3d-transition-metal HEAs (based on Fe, Co, Ni, Cr, Mn, and similar elements), refractory HEAs (based on high-melting-point elements such as Nb, Ta, Mo, W, V, and Zr), lightweight HEAs (incorporating low-density elements such as Al, Mg, Li, and Ti), precious-metal HEAs, and rare-earth HEAs [9].

2.2. Phase-Formation Rules and Predictive Parameters

Because reliable a priori prediction of the resulting phase (single-phase solid solution versus multiphase or intermetallic-containing microstructure) remains challenging given the enormous compositional space available, empirical parameters — including the atomic-size mismatch parameter (δ), the valence electron concentration (VEC), and the mixing enthalpy (ΔHmix) — have been developed to provide practical, if imperfect, design guidance [7,10]. More recently, CALPHAD-based thermodynamic modelling and machine-learning-assisted composition screening have been used to navigate this compositional space more systematically than exhaustive experimental trial-and-error permits [11,12].

2.3. Eutectic High Entropy Alloys

Eutectic high entropy alloys (EHEAs), first proposed by Lu and co-workers, combine a soft, ductile FCC solid-solution phase with a hard, strong BCC or intermetallic phase in a fine eutectic microstructure obtained directly from as-cast processing, offering a practical route to simultaneously high strength and adequate castability without the need for extensive post-processing thermomechanical treatment [13]. EHEAs have attracted particular attention for elevated-temperature structural applications owing to this combination of processability and mechanical performance [9].

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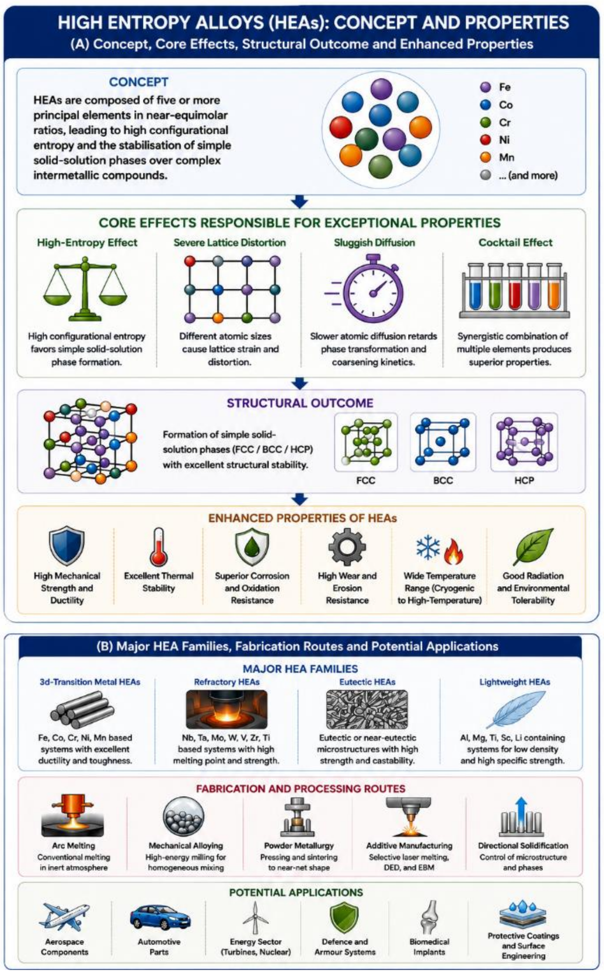

Figure 1. Overview of the design principles, properties, and applications of high entropy alloys (HEAs).

3. FABRICATION AND PROCESSING TECHNIQUES

3.1. Liquid-State Processing

Vacuum arc melting remains the most widely used HEA synthesis route owing to its simplicity, cost-effectiveness, and compatibility with conventional metallurgical infrastructure, involving melting of elemental charges under an inert or vacuum atmosphere followed by casting into the desired geometry; related liquid-state routes include induction melting, Bridgman directional solidification, and laser-based melting [14]. Processing-route comparisons indicate that the specific phase balance and mechanical response achieved through liquid-state processing are highly sensitive to both alloy composition and thermal history, including cooling rate [14].

3.2. Mechanical Alloying and Powder Metallurgy

Mechanical alloying, in which elemental powders are combined through high-energy ball milling, is a non-equilibrium solid-state synthesis route capable of producing nanostructured HEA powders directly, avoiding the segregation issues that can accompany solidification from the melt, particularly for elements of widely differing melting points [15]. Powder metallurgy routes — typically combining mechanical alloying or blended elemental powders with hot isostatic pressing or spark plasma sintering (SPS) — avoid the coarse dendritic microstructures characteristic of arc-melted alloys and can improve compositional homogeneity; comparative studies indicate that SPS-processed HEAs can achieve substantially higher yield and tensile strength than arc-melted counterparts of the same nominal composition owing to the finer, more homogeneous resulting microstructure [16,17].

3.3. Additive Manufacturing

Additive manufacturing techniques, particularly selective laser melting, have more recently been applied to HEA fabrication, offering near-net-shape processing capability alongside microstructural refinement from the rapid solidification rates inherent to the process, and are increasingly explored as a route to complex-geometry HEA components that would be difficult to achieve via conventional casting or powder-consolidation routes [14,17].

4. MICROSTRUCTURAL EVOLUTION AND MECHANICAL PROPERTIES

4.1. Solid-Solution Strengthening and Lattice Distortion

The mechanical performance of single-phase HEAs arises substantially from solid-solution strengthening driven by lattice distortion from atomic-size mismatch among the constituent elements, compounded by sluggish diffusion, which retards the coarsening of strengthening microstructural features during thermal or mechanical service [1,4]. FCC-structured HEAs such as CrMnFeCoNi generally exhibit excellent ductility and fracture toughness, including at cryogenic temperature, where the Cantor alloy has been shown to exhibit

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exceptional fracture resistance attributed to deformation-induced nanoscale twinning that activates progressively with decreasing temperature [18]. BCC-structured HEAs, by contrast, typically offer higher strength but reduced room-temperature ductility, motivating research into dual-phase and heterogeneous microstructures that combine the favourable attributes of both crystal structures [19].

4.2. Dual-Phase and Metastability Strategies

Metastable dual-phase HEAs engineered to undergo transformation-induced plasticity (TRIP) during deformation have been shown to overcome the classical strength-ductility trade-off, with one widely cited study reporting simultaneous high strength and high ductility in a dual-phase HEA through phase-transformation-mediated strain hardening [19]. Real-time synchrotron observations of TRIP-induced ultrahigh strain hardening in a dual-phase CrMnFeCoNi-based HEA have further clarified the microstructural mechanisms underpinning this behaviour [20].

4.3. Refractory and High-Temperature Behaviour

Refractory HEAs, based on elements such as Nb, Ta, Mo, W, V, Zr, and Ti, were first proposed in 2010 and have since attracted sustained interest for their high strength retention at elevated temperature, positioning them as candidate replacements for conventional Ni-based superalloys in gas-turbine hot-section and aerospace propulsion applications [21,22]. A dedicated review of HEA high-temperature applicability notes that HEA-based high-entropy superalloys (HESAs), such as AlCoCrFeNiTi-based compositions, occupy a compositional space distinct from both conventional Ni-based superalloys and equimolar HEAs, offering a broad, largely unexplored design space for further high-temperature alloy development [22]. Development and exploration of refractory HEAs for structural applications more broadly has been extensively reviewed by Senkov and co-workers [23,24].

4.4. Table of Representative HEA Property Trends

Table 1: Representative high entropy alloy families and their notable reported mechanical or microstructural properties.

HEA Family	Representative System	Notable Reported Property	Ref.
3d-transition FCC	CrMnFeCoNi (Cantor alloy)	Exceptional cryogenic fracture toughness via twinning	18
Dual-phase / metastable	Fe-Mn-Co-Cr-based TRIP HEA	Overcomes strength-ductility trade-off	19,20
Refractory BCC	NbMoTaW / VNbMoTaW	High strength retention above 1000°C	21,23
High-entropy superalloy	AlCoCrFeNiTi-based HESA	Distinct compositional space vs. Ni-superalloys	22
Eutectic HEA	AlCoCrFeNi2.1-type	As-cast FCC+BCC eutectic; strength-castability balance	13
Al-containing 3d HEA	AlxCrFeCoNiSi	Microhardness 598→909 HV with increasing Al content	25

5. WEAR AND CORROSION BEHAVIOUR

Beyond bulk mechanical strength, HEAs have attracted considerable attention for their wear and corrosion performance, which is critical for applications in nuclear reactors, gas turbines, and aeronautical hardware where erosive and corrosive environments frequently act in synergy [25]. A comprehensive review of wear, corrosion, and wear-corrosion synergy in HEAs found that alloying-element selection and secondary-phase formation (for example, Cr3Si precipitation in AlxCrFeCoNiSi alloys) can be tuned to raise microhardness from 598 HV to 909 HV with increasing aluminium content, directly improving wear resistance through a solid-solution and precipitation-strengthening mechanism [25]. Environmental corrosion behaviour and its underlying mechanisms in HEAs have been separately reviewed, noting that passive-film stability and elemental partitioning between phases are the dominant factors controlling corrosion resistance in aggressive chloride-containing media [26]. Laser-cladding of AlxCrFeCoNiCu HEA coatings onto aluminium substrates has demonstrated that HEA coatings can simultaneously deliver improved microhardness, wear resistance, and corrosion resistance relative to the uncoated substrate, illustrating a practical route to extending HEA benefits to conventional structural materials without requiring bulk HEA components [27]. Erosion-corrosion studies comparing HEAs against conventional stainless steel (SS316L) have shown that HEAs can achieve markedly lower corrosion rates under combined sand-slurry and chloride exposure, although the relative erosion

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resistance depends on the specific hardness achieved by each material under the test conditions [28].

6. APPLICATIONS AND FUNCTIONAL POTENTIAL

The combination of high strength, thermal stability, and corrosion/wear resistance positions HEAs as candidate materials across a broad application landscape. In structural roles, HEAs are being explored for aerospace and automotive components, high-temperature gas-turbine hot-section hardware, and protective wear- and corrosion-resistant coatings for tooling and drilling equipment [22,27]. Beyond bulk structural use, HEAs are increasingly explored as functional materials: their tunable electrochemical and biocompatibility characteristics have motivated investigation of HEA orthopaedic and dental implant components, their compositional flexibility has been exploited in battery, fuel-cell, and supercapacitor electrode materials, and their favourable electromagnetic characteristics have opened a distinct research direction in electromagnetic-interference shielding and multispectral stealth coatings [29,30]. A recent review of HEA thermodynamic design and computational modelling strategies further highlights the breadth of this emerging application landscape across the aerospace, automotive, energy, and biomedical sectors, while also cataloguing the empirical design limitations and processing complexities that continue to constrain translation from laboratory demonstration to deployed components [11].

7. CHALLENGES AND LIMITATIONS

7.1. Phase Prediction and Compositional Complexity

The enormous compositional space available when combining five or more principal elements makes reliable a priori phase prediction a persistent challenge; empirical parameters such as δ, VEC, and ΔH_{mix} provide useful but imperfect guidance, motivating continued development of CALPHAD and machine-learning-assisted composition-screening tools [7,11,12].

7.2. Processing Scalability and Cost

Many of the highest-performing HEA compositions reported in the literature have been synthesised at laboratory scale via arc melting or mechanical alloying, and scaling these processes to industrially relevant component sizes while retaining the fine, controlled microstructures responsible for the reported properties remains an open processing challenge, compounded by the generally higher raw-material cost of multi-principal-element compositions relative to conventional single-base alloys [16,17].

7.3. Property Database and Standardisation Gaps

Because HEA mechanical, wear, and corrosion properties are highly sensitive to processing route and minor compositional variation, the field currently lacks the comprehensive, standardised property databases and design allowables that are routinely available for conventional structural alloys, complicating direct engineering design comparisons across independently reported studies [11].

8. FUTURE DIRECTIONS

Three directions appear most likely to advance HEAs toward broader industrial deployment. First, continued integration of computational thermodynamics with machine-learning-assisted composition screening should substantially reduce the experimental burden of navigating the HEA compositional space and improve phase-prediction reliability [11,12]. Second, continued development of scalable powder-metallurgy and additive-manufacturing processing routes is needed to translate laboratory-scale results into components of industrially relevant size and geometry [16,17]. Third, systematic, application-specific optimisation — tailoring refractory HEAs for high-temperature turbine hardware, wear- and corrosion-resistant HEAs for protective coatings, and biocompatible HEAs for implant components — rather than pursuit of generically "best" compositions, is likely to yield the most direct route to near-term industrial adoption [22,27,29].

9. CONCLUSION

The principal conclusions of this compiled review are as follows:

• High entropy alloys extend conventional alloy design by combining five or more principal elements in near-equimolar ratios, with the high-entropy effect, lattice distortion, sluggish diffusion, and cocktail effect collectively underpinning their exceptional mechanical, wear, and corrosion performance.

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• Arc melting, mechanical alloying, powder metallurgy, and additive manufacturing each offer distinct advantages for HEA fabrication, with powder-consolidation and additive routes generally providing finer, more homogeneous microstructures than conventional casting.

• FCC-structured HEAs such as CrMnFeCoNi offer exceptional ductility and cryogenic fracture toughness, BCC-structured refractory HEAs offer superior high-temperature strength retention, and dual-phase/metastable HEA designs can overcome the classical strength-ductility trade-off through transformation-induced plasticity.

• HEAs demonstrate strong wear and corrosion resistance that can be further tuned through alloying-element selection and secondary-phase engineering, supporting applications in protective coatings alongside bulk structural use.

• Beyond structural applications, HEAs show growing functional potential in biomedical implants, energy storage electrodes, and electromagnetic shielding, broadening their relevance well beyond the aerospace and automotive sectors that originally motivated the field.

• Phase-prediction reliability, processing scalability and cost, and the absence of standardised property databases remain the principal barriers to industrial-scale HEA adoption, and should be prioritised alongside application-specific compositional optimisation in future research.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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