THE PERFORMANCE OF HIGH-ENTROPY ALLOYS IN AGGRESSIVE ENVIRONMENTS

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Rezumat. *Aliajele cu entropie înaltă (HEAs) sunt materiale avansate, compuse din multiple elemente principale în proporții aproape echiatomice. HEAs specializate prezintă performanțe excepționale în ceea ce privește rezistența la temperaturi ridicate, rezistența la oxidare și la fluaj, făcându-le viabile pentru aplicații aerospațiale și nucleare. HEAs biomedicale au apărut cu o rezistență promițătoare la coroziune, biocompatibilitate și proprietăți mecanice potrivite pentru implanturi. În ciuda progreselor semnificative în optimizarea caracteristicilor aliajelor, există în continuare provocări legate de cost, de prezicerea precisă a fazelor și de producția la scară largă. Se anticipează că progresele viitoare vor fi posibile prin strategii interdisciplinare care să includă modelare avansată, învățare automată și fabricare aditivă.*

Abstract. *High-entropy alloys (HEAs) are advanced materials composed of multiple principal elements in near-equiatomic ratios. Specialized HEAs display exceptional performance in high-temperature strength, oxidation resistance, and creep resistance, making them viable for aerospace and nuclear applications. Biomedical HEAs have emerged with promising corrosion resistance, biocompatibility, and mechanical properties suitable for implants. Despite significant progress in optimizing alloy characteristics, challenges remain regarding cost, accurate phase prediction, and scalable manufacturing. Future advancements are expected through interdisciplinary strategies incorporating advanced modelling, machine learning, and additive manufacturing.*

Keywords: High-Entropy Alloys (HEAs); multicomponent systems; mechanical properties; corrosion resistance; biomedical alloys.

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1. Introduction: The innovative nature of high-entropy alloys

High-entropy alloys (HEAs) have garnered growing interest in materials science due to their multi-element compositions and potential for great mechanical performance [1–4]. Unlike traditional alloys, which are typically based on one primary element alloyed with others in smaller quantities to enhance specific properties [5], HEAs consist of five or more elements in nearly equal atomic ratios, offering a fundamentally different approach to alloy design [6–8]. While traditionally termed high-entropy alloys, it should be noted that the literature also utilizes broader terms such as multi-principal element alloys and complex concentrated alloys to more accurately describe alloys with significant but not necessarily dominant configurational entropy.

Here is the second paragraph. Yeh and collaborators were among the first to emphasize the role of high mixing entropy in the stabilization of simple solid solution phases, primarily face-centred cubic (FCC) and body-centred cubic (BCC), while suppressing the formation of complex intermetallic compounds. Their studies highlighted notable features such as refined microstructures, improved mechanical properties, and increased corrosion resistance, positioning HEAs as a new class of advanced materials [9–11].

Based on their composition and intended applications, HEAs can be broadly categorized into metallic and ceramic types. Metallic HEAs include Cantor-type alloys, such as the FeCoNiMnCr series, as well as refractory compositions based on elements like Ti, Mo, Ta, Zr, Hf, V, and Nb, designed for high-temperature and corrosive environments due to their excellent mechanical strength. Ceramic HEAs, comprising nitrides and carbides of transition metals, offer high thermal stability, corrosion resistance, and hardness, making them suitable for extreme applications [12,13].

A more detailed classification of HEAs divides them into seven main families, depending on the nature of the constituent elements: (i) 3d transition metals (e.g., Cr, Ni, Fe, Mn, Cu, Al, Ti, V), which dominate HEA research; (ii) refractory metals (e.g., Mo, Cr, Hf, Ti, Ta, Nb, W, V, Zr); (iii) lightweight metals (e.g., Mg, Al, Li, Be, Sn, Zn, Si, Ti, Sc); (iv) lanthanides or 4f transition metals (e.g., Gd, Dy, Tb, Lu, Tm, Y); (v) brasses and bronzes (e.g., Al, Cu, Mn, Ni, Sn, Zn); (vi) precious metals (e.g., Ag, Au, Co, Cr, Cu, Ni, Pd, Pt, Rh, Ru); and (vii) interstitial compounds (e.g., B, C, N). However, due to the large variety of possible element combinations, many HEAs defy strict classification, highlighting the field's complexity and potential for innovation [9,14]. While the previous classification is based on chemical families, HEAs can also be grouped by their intended functionality and application domain. Figure 1 summarizes this functional categorization, illustrating how different classes of HEAs align with key technological applications.

Despite their remarkable potential, HEAs continue to encounter the critical challenge of balancing strength and ductility. Additional challenges include deciphering intricate phase behaviours, managing production costs, and ensuring reliable performance under real-world conditions. Addressing these challenges through integrated experimental and computational approaches forms the core of ongoing research.

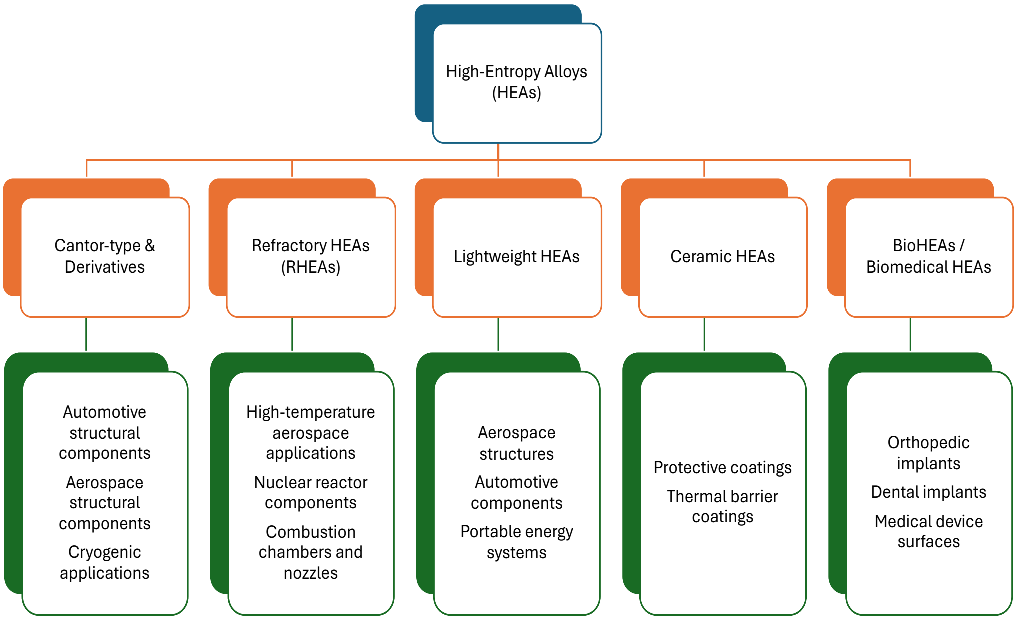

Figure 1. Functional classification of high-entropy alloys (HEAs) highlighting their primary application areas

In recent years, alloys incorporating refractory elements have stood out for their ability to form stable high-temperature phases with superior strength, creep resistance, and oxidation tolerance [15–17].Within this landscape, refractory high-entropy alloys (RHEAs) have emerged as a particularly promising group, capable of outperforming conventional materials such as Ni-based superalloys and silicon carbide in extreme conditions [18–20]. Their application potential spans sectors like nuclear energy and aerospace, where resistance to high-temperature degradation is critical [21].

2. Fundamentals of high-entropy alloys

Although multicomponent alloys are frequently referred to as “high-entropy alloys,” the term does not always reflect their thermodynamic characteristics. In many cases, these alloys do not exhibit particularly high configurational entropy, and the formation of a limited number of phases cannot be solely attributed to entropy stabilization effects [5]. Furthermore, the early assumption that HEAs must consist of singlephase solid solutions (BCC, FCC, or HCP) has been increasingly questioned. Intermetallic compounds, once considered undesirable, are now understood to play a potentially beneficial role in certain alloy systems [22,23].
The distinctiveness of HEAs arises from their atomic-level structural complexity. In contrast to conventional materials—where unique properties are achieved

through controlled introduction of defects—HEAs inherently possess chemical disorder due to the inclusion of multiple elements in comparable atomic ratios. This results in a departure from traditional design approaches based on the Hume-Rothery rules and leads to a highly varied local atomic environment. The resulting lattice is characterized by differences in atomic size, electronegativity, valence state, and magnetic moment, which generate irregular nearest-neighbour arrangements, non-uniform bond lengths, and distorted charge distributions [24].

In addition to entropy, three other key effects are commonly used to describe the behaviour of HEAs: sluggish diffusion, lattice distortion, and the cocktail effect [22,25,26]. The sluggish diffusion effect refers to the reduced mobility of atoms, attributed to the presence of diverse bonding environments that increase the activation energy required for atomic migration. Lattice distortion results from asymmetric bonding between atoms of different sizes and electronic structures, affecting various physicochemical properties. The cocktail effect denotes the possibility that the combination of elements within an alloy may lead to properties not exhibited by the individual constituents. In some cases, the collective effect may even be opposite to that expected from a simple weighted average, such as when the addition of a soft element contributes to increased hardness [27,28].

Recent perspectives have further refined the HEA concept, suggesting that their exceptional properties may also derive from other factors such as short-range ordering, stacking fault energy (SFE), lattice misfit, and anti-phase boundary energy (APBE). These parameters have emerged as essential design criteria, especially in systems where entropy-driven stabilization is insufficient to explain phase formation or mechanical behaviour. For example, low SFE has been linked to enhanced ductility via transformation-induced or twinning-induced plasticity (TRIP/TWIP), while lattice misfit and APBE play critical roles in strengthening mechanisms by impeding dislocation motion and stabilizing ordered precipitates. This broader framework enables the design of alloys with tailored microstructures and targeted performance, even in non-equiatomic compositions, thus expanding the landscape of high-entropy materials beyond their original formulation [29].

3. Performance under aggressive conditions

Understanding the relationship between the structure and properties of alloys is essential for identifying their potential applications [30–32]. HEAs are typically characterized by the formation of simple solid solution phases such as face centred cubic (FCC), body centred cubic (BCC), or hexagonal close packed (HCP), as well as by their capacity to form intermetallic compounds [14]. The presence of fewer phases compared to conventional alloys is largely attributed to the stabilizing effect of high mixing entropy [33–35]. This stabilization arises from differences in atomic properties, including electronic configurations, electronegativities, and oxidation states, which contribute to a distorted energy landscape and locally distinct chemical environments [24,36]. These structural features have a direct impact on key mechanical properties such as strength, ductility, and hardness.

Despite their promising properties, HEAs often face limitations related to the strength–ductility trade-off, which remains a major challenge for their use in structural applications [37–41]. For instance, FCC HEAs are typically characterized by good ductility but limited tensile strength at room temperature, whereas BCC HEAs offer higher strength but suffer from low plasticity and increased brittleness, making them susceptible to early cracking [42,43].

Some HEAs also exhibit improved thermal conductivity, a property that is particularly beneficial in nuclear reactor components where efficient heat transfer is required. Their combined characteristics, such as high tensile strength, ductility, and hardness—make them suitable for demanding nuclear applications, including reactor pressure vessels and fuel cladding [44–47]. Furthermore, the atomic structure and high configurational entropy of HEAs contribute to enhanced resistance to radiation damage, which supports their long-term structural integrity in such environments [47,48].

Early examples of RHEAs, such as the NbMoTaW series, demonstrated excellent yield strength at elevated temperatures. However, they were also characterized by high density and poor ductility. These limitations led to the development of second-generation RHEAs, in which heavier elements (e.g., W, Mo, Ta) were partially replaced by lighter alternatives such as Ti, V, Zr, and Cr to tailor specific properties. Alloys incorporating Al or Si were particularly successful, achieving densities below 7 g/cm^3 in some cases [49]. Although low density is not always a requirement for refractory materials, it can offer advantages in applications such as aerospace turbines and jet engines, where weight reduction is beneficial [50].

An overview of current and emerging applications for HEAs in aggressive environments is provided in Table 1. This summary highlights the types of HEAs suited for specific applications and the main properties associated with each case. Applications range from nuclear energy and aerospace to wear-resistant coatings and biomedical devices, reflecting the versatility and adaptability of HEAs across multiple sectors. The table also illustrates how tailoring the elemental composition and microstructure of HEAs allows for optimization of critical properties such as strength, thermal stability, creep resistance, resistance to corrosion, and biocompatibility.

Table 1. Applications of HEAs in aggressive conditions

HEA Type	*Properties and performance*	*Application*	*Ref.*
RHEAs	Retain mechanical strength at temperatures reaching 60–70% of their melting point, with effective operation in the range of 1363–1941 K	High-temperature aerospace applications	[14,51,52]
$Al_{0.5}CoCrFeNiTi_{0.1}$ HEA	Exhibits exceptional mechanical performance from cryogenic (−160 °C) to high temperatures (up to 800 °C), with UTS ranging from 1398 MPa (−160 °C) to 332.7 MPa (800 °C), due to FCC matrix and L21 precipitate strengthening	Cryogenic to high-temperature structural applications	[53]
Second-Generation RHEAs	Exhibit a balanced combination of strength and ductility, reduced density, and sustained mechanical performance at elevated temperatures	High-stress turbine blades	[49]
Refractory Amorphous High-Entropy Alloys (RAHEAs)	Enhanced phase stability, exceptional performance during high-temperature annealing and irradiation, and potential self-healing behaviour via nanoprecipitate reassembly that improves radiation resistance	Extreme environment applications	[52]
Cantor Alloys & Derivatives	High synergy of strength and ductility across a wide temperature range, facilitated by low stacking fault energy that promotes twinning and the TRIP effect, effectively overcoming the conventional strength–ductility trade-off through advanced alloying and processing strategies	Automotive and aerospace structural components	[42,54]
CoCrNi MEA (ultrafine-grained microstructure)	Exceptional strength and plasticity under dynamic and high-temperature loading, enabled by ultrafine grains and stable nano-twins; outperforms cast counterparts with 300% higher yield strength	Impact-resistant aerospace and defense components	[55]
Lightweight RHEAs (LRHEAs)	Stable single-phase BCC structure with excellent high-temperature phase stability and mechanical strength (yield strength up to 1763 MPa after annealing at 600 °C)	High-temperature aerospace applications	[56]
Light-weight metastable HEAs (LMH)	Combine low density with high specific strength and substantial ductility, enabled by TRIP-assisted dual-phase stability	Lightweight structural applications	[57]
MoNbWTaC HEA	Carbide-reinforced ultrafine eutectoid structure provides high yield strengths of 1.17 GPa at 1473 K and 0.92 GPa at 1673 K, with excellent thermal stability	Combustion chambers and nozzles for aerospace and weapons systems	[58]
REE-doped AlCoCrFeMo HEA Coating	Exhibits ultra-high strength, excellent abrasive wear and erosion resistance due to grain refinement and solid solution strengthening by rare earth elements	Protective coatings for aerospace and defence components	[59]

Beyond structural and high-temperature applications, HEAs have also shown great potential in the biomedical field [60]. Their performance in corrosive environments and compatibility with biological systems have made them promising candidates for use in medical implants [61–64]. One extensively studied composition is the TiZrHfNbTa alloy, prepared via arc melting from high-purity elemental precursors. Yang et al. investigated its corrosion behaviour in Hank’s solution and evaluated its biocompatibility using MC3T3-E1 pre-osteoblasts, in comparison with the conventional Ti6Al4V alloy. The TiZrHfNbTa alloy exhibited comparable corrosion resistance and biocompatibility, without the cytotoxic risks associated with Al and V ion release. Additionally, it demonstrated a lower elastic modulus (~80 GPa) than Ti6Al4V (~110 GPa), potentially reducing stress shielding in orthopaedic applications [65].
Subsequent studies have explored surface modification strategies to further enhance the performance of TiZrHfNbTa. Zhang et al. applied plasma electrolytic oxidation (PEO) at varying voltages and observed improvements in corrosion resistance and wear without compromising cell adhesion or proliferation [66]. Another widely investigated surface treatment is anodization in fluoride-containing electrolytes, that leads to the formation of self-organized oxide nanotubes [67,68]. Berger et al. demonstrated that this technique improves the corrosion resistance, mechanical performance, and bioactivity on the same TiZrHfNbTa substrate [69].
Several BioHEAs are presented in Table 2 along with their structure, mechanical and electrochemical properties.

Table 2. Structure and properties of BioHEAs

Alloy	*Structure*	*Mechanical properties*	*Resistance to corrosion*	*Ref.*
$Ti_{49}Zr_{20}Hf_{15}Al_{10}Nb_{6}$	Single β-phase (BCC)	HV – 314 E – 83.9 GPa Super elasticity: recoverable strain ~3.8% Yield strength ~650 MPa	Corrosion potential (Ecorr) − -0.177 V; current density (Icorr) − 0.163 μA/cm² in Hank’s solution	[70]
$Ti_{40}Zr_{40}Nb_{5}Ta_{12}Sn_{3}$	BCC	HV – 336 E ~ 86 GPa	Ecorr: − 0.314 V; Icorr − 2.61 × 10^{-7} A/cm² in artificial saliva	[71]
Ti40Zr20Hf10Nb20Ta10	BCC	HV – 294 E – 86.4 GPa	Polarization behaviour in 3.5% NaCl solution reveals substantially superior corrosion resistance compared to commercially pure titanium (CP-Ti)	[72]

$Ti_{35}Zr_{35}Nb_{20}Ta_5Ag_5$	BCC solid solution	Microhardness – 4.38–5.35 GPa	Icorr ~2 orders of magnitude lower than CP-Ti in artificial saliva	[73]
Ti20Zr20Hf20Nb20Ta20	BCC solid solution	HV – 320 E – 79 GPa	Corrosion rate in Hank's solution − 5.5E-4 mm/year	[74]
Ti25Zr25Hf25Nb12.5Ta 12.5		HV – 293 E – 68 GPa	Corrosion rate in Hank's solution − 8.8E-4 mm/year	
Ti27.78Zr27.78Hf27.78 Nb8.33Ta8.33		HV – 287; E – 56 GPa	Corrosion rate in Hank's solution − 9.3E-4 mm/year	
$Mg_{60}Ti_{24.24}Zn_{9.66}Nb_{6.1}$	HCP + BCC	UTS – 181 MPa; Yield strength – 132 MPa	Corrosion rate − 0.86 ± 0.11 mm/year (lower than AZ31 and pure Mg)	[75]

4. Recent developments and future directions

The evolution of high-entropy alloys has developed through distinct generational stages. The first-generation HEAs primarily consisted of single-phase solid solutions with FCC or BCC structures, based largely on 3d transition metals and refractory elements. These early compositions provided the foundational understanding of high-entropy alloy behaviour and stability. In contrast, second-generation HEAs have introduced more complex, multiphase microstructures that contribute to enhanced mechanical and functional properties. This shift has also expanded the range of applications, demonstrating the versatility of HEAs across diverse operating conditions [76–80].

In parallel, the predictive capabilities of alloy design have been significantly improved by combining thermodynamic models with electronic structure calculations and high-throughput computational tools. CALPHAD, DFT, and MD simulations have been employed to explore phase stability, mixing enthalpy, lattice distortion, and diffusion behaviour. However, the vast compositional landscape of HEAs, characterized by competing entropic and enthalpic effects, often challenges the reliability of classical rules. To address this, novel descriptors such as atomic packing efficiency, valence electron concentration, and normalized strain energy have been introduced, offering refined guidelines for identifying stable and functional alloy compositions [81].

Machine learning (ML) has emerged as a transformative tool in HEA discovery, offering a scalable framework for exploring complex composition–property relationships beyond the reach of traditional methods. Supervised ML models have demonstrated remarkable accuracy in predicting phase formation, stacking fault energies, and mechanical strength using descriptors like radius mismatch, ΔH_{mix}, VEC, and electronegativity differences. Advanced frameworks incorporating ensemble methods, interpretability techniques, and hybrid physical–data-driven models have accelerated the research of novel HEAs with target performance metrics, while addressing long-standing challenges such as data scarcity and limited transferability in high-dimensional design spaces [82].

Among the most promising directions in HEA research is the development of RHEAs, which have demonstrated exceptional high-temperature strength, oxidation resistance, and corrosion resilience. These materials are increasingly seen as viable alternatives to Ni-based superalloys for demanding applications in aerospace, nuclear, and energy sectors. Recent studies have also emphasized the role of advanced manufacturing techniques—particularly additive manufacturing and powder metallurgy—in enabling more efficient synthesis of RHEAs with refined microstructures and enhanced performance. Despite their outstanding properties, RHEAs still face challenges related to creep behaviour and production costs, highlighting the need for continued innovation in alloy design and processing technologies [83].

To advance the design and optimization of these materials, researchers have increasingly adopted integrated approaches that combine experimental techniques with computational tools and data-driven methods. These strategies allow for the rapid identification of promising alloy systems tailored to meet specific performance requirements, thereby accelerating the discovery and development of next-generation materials [84–89].

5. Concluding remarks

High-entropy alloys have emerged as an innovative class of materials, distinguished by their complex, multi-element compositions and the potential to deliver superior performance in demanding conditions. This review has covered the fundamental principles underlying HEAs, including configurational entropy, sluggish diffusion, lattice distortion, and the cocktail effect, and highlighted how these factors directly influence their properties and application capabilities.

Significant advancements have been made, particularly with refractory HEAs (RHEAs), which show outstanding mechanical strength, oxidation resistance, and radiation tolerance in extreme environments. Additionally, substantial progress has been achieved in the development of biocompatible HEAs (BioHEAs), demonstrating excellent corrosion resistance, mechanical compatibility, and biocompatibility, thus expanding their potential applications in the biomedical field.

Nevertheless, HEAs still face notable challenges, especially in balancing strength and ductility, predicting complex phase formations, and controlling production costs.

To effectively address these challenges, future research needs more integrated and interdisciplinary approaches, combining computational modelling, machine learning, and advanced manufacturing processes. Expanding the scope of research into lightweight HEAs and biomedical applications will further extend their practical relevance.

Continued collaborative efforts across various scientific and engineering fields will undoubtedly unlock the full potential of HEAs, transforming them from novel experimental alloys into widely utilized materials that effectively meet diverse technological demands in sectors such as aerospace, nuclear energy, and biomedicine.

REFERENCES

[1] C. Cheng and Y. Zou, "Accelerated discovery of nanostructured high-entropy alloys and multicomponent alloys via high-throughput strategies," Prog. Mater. Sci., vol. 151, p. 101429, May 2025.

[2] S. Wu et al., "Controllable preparation of metal-based lubrication coatings in extreme environmental applications," Mater. Des., vol. 241, no. March, p. 112922, May 2024.

[3] D. Dong et al., "Enhanced mechanical properties of high pressure solidified CoCrFeNiMo0.3 high entropy alloy via nano-precipitated phase," Intermetallics, vol. 166, no. January, p. 108192, 2024.

[4] G. Fu et al., "Development of High-Entropy Shape-Memory Alloys: A Review," Metals (Basel)., vol. 13, no. 7, p. 1279, Jul. 2023.

[5] B. Cantor, "Multicomponent and high entropy alloys," Entropy, vol. 16, no. 9, pp. 4749–4768, 2014.

[6] D. B. Miracle, "High entropy alloys as a bold step forward in alloy development," Nat. Commun., vol. 10, no. 1, pp. 1–3, 2019.

[7] W. Xing, Z. Yu, C. Liu, and H. Zhao, "In-situ EBSD investigation of superior strength-ductility synergy achieved through multiscale heterogeneous structure design in Al0.25FeCoNiVTi0.1 high-entropy alloy," Mater. Sci. Eng. A, vol. 923, p. 147721, Feb. 2025.

[8] G. Abrantes, B. Alves, D. Gatões, R. Batalha, and P. Freitas Rodrigues, "Design of non-equiatomic low-density alloys inspired by modified high-entropy shape memory alloy," J. Mater. Res. Technol., vol. 36, pp. 72–79, May 2025.

[9] S. A. Krishna, N. Noble, N. Radhika, and B. Saleh, "A comprehensive review on advances in high entropy alloys: Fabrication and surface modification methods, properties, applications, and future prospects," J. Manuf. Process., vol. 109, no. December 2023, pp. 583–606, 2024.

[10] M. Naseri et al., "Enhancing the mechanical properties of high-entropy alloys through severe plastic deformation: A review," J. Alloy. Metall. Syst., vol. 5, no. November 2023, p. 100054, 2024.

[11] Y. Wang, J. Zhang, T. Wu, and G. Huang, "An all-around way to analyze the corrosion behavior and the potential applications of high-entropy alloys coating," Ceram. Int., vol. 50, no. 4, pp. 5893–5913, 2024.

[12] A. Sharma, "High Entropy Alloy Coatings and Technology," Coatings, vol. 11, no. 4, p. 372, Mar. 2021.

[13] A. Hilhorst, J. Leclerc, T. Pardoen, P. J. Jacques, L. Noels, and V. Nguyen, "Ductile fracture of high entropy alloys : From the design of an experimental campaign to the development of a micromechanics-based modeling framework," Eng. Fract. Mech., vol. 275, no. September, p. 108844, 2022.

[14] D. B. Miracle and O. N. Senkov, “A critical review of high entropy alloys and related concepts,” Acta Mater., vol. 122, pp. 448–511, 2017.
[15] Y. F. Yang et al., “High entropy alloys: A review of preparation techniques, properties and industry applications,” J. Alloys Compd., vol. 1010, no. October 2024, p. 177691, 2025.
[16] N. V. Abhijith, S. Phutela, D. Kumar, and D. Kalyanasundaram, “Transitional and refractory elements-based high entropy alloy developed through mechanical alloying and microwave sintering: Tribological and corrosion responses,” Vacuum, vol. 222, p. 113061, Apr. 2024.
[17] Z. Xie et al., “Effect of refractory elements on the microstructure and mechanical property of medium-entropy alloys fabricated by additive manufacturing,” Mater. Today Commun., p. 112243, Mar. 2025.
[18] M. A. Melia et al., “High-throughput additive manufacturing and characterization of refractory high entropy alloys,” Appl. Mater. Today, vol. 19, p. 100560, 2020.
[19] S. Rodriguez, A. Kustas, and G. Monroe, “Metal Alloy and RHEA Additive Manufacturing for Nuclear Energy and Aerospace Applications SAND 2020-7244,” no. July, 2020.
[20] J. Čížek, J. Kalivodová, M. Janeček, J. Stráský, O. Srba, and A. Macková, “Advanced structural materials for gas-cooled fast reactors—a review,” Metals (Basel)., vol. 11, no. 1, pp. 1–23, 2021.
[21] S. Veselkov, O. Samoilova, N. Shaburova, and E. Trofimov, “High-temperature oxidation of high-entropic alloys: A review,” Materials (Basel)., vol. 14, no. 10, 2021.
[22] D. B. Miracle and O. N. Senkov, “A critical review of high entropy alloys and related concepts,” Acta Mater., vol. 122, pp. 448–511, 2017.
[23] R. Li, T. Huang, J. Zhang, C. Jiang, Y. Zhang, and P. K. Liaw, “Microstructures, Mechanical Behavior, and Radiation Damage of (TiVCr)x-(TaW)1-x Binary System High-Entropy Alloy Films,” Metals (Basel)., vol. 12, no. 5, pp. 1–18, 2022.
[24] D. S. Aidhy, “Chemical randomness, lattice distortion and the wide distributions in the atomic level properties in high entropy alloys,” Comput. Mater. Sci., vol. 237, no. February, p. 112912, 2024.
[25] M. H. Tsai and J. W. Yeh, “High-entropy alloys: A critical review,” Mater. Res. Lett., vol. 2, no. 3, pp. 107–123, 2014.
[26] D. Castro, P. Jaeger, A. C. Baptista, and J. P. Oliveira, “An Overview of High-Entropy Alloys as Biomaterials,” Metals (Basel)., vol. 11, no. 4, p. 648, Apr. 2021.
[27] S. K. Dewangan, A. Mangish, S. Kumar, A. Sharma, B. Ahn, and V. Kumar, “A review on High-Temperature Applicability: A milestone for high entropy alloys,” Eng. Sci. Technol. an Int. J., vol. 35, no. xxxx, p. 101211, Nov. 2022.
[28] D. Patel, “Development of Novel Low Activation Refractory High Entropy Alloys for Nuclear Fusion Applications Dhinisa Patel,” 2021.
[29] J. M. Torralba, A. Meza, S. V. Kumaran, A. Mostafaei, and A. Mohammadzadeh, “From high-entropy alloys to alloys with high entropy: A new paradigm in materials science and engineering for advancing sustainable metallurgy,” Curr. Opin. Solid State Mater. Sci., vol. 36, p. 101221, May 2025.
[30] J. Li et al., “Non-isothermal crystallization behavior of Cr50Fe6Co7Mo14C15B6Y2 metallic glass with super high content of Cr and integrated merits,” J. Mater. Res. Technol., vol. 32, pp. 470–477, Sep. 2024.
[31] R. Nartita, D. Ionita, and I. Demetrescu, “A Modern Approach to HEAs: From Structure to Properties and Potential Applications,” Crystals, vol. 14, no. 5, pp. 1–20, 2024.
[32] R. Nartita, A. B. Stoian, D. Ionita, and I. Demetrescu, “Thermal effects on the mechanical, electrochemical, and surface properties of a Ti–20Zr–5Ta–2Ag alloy for potential industrial and biomedical applications,” J. Mater. Res. Technol., vol. 35, pp. 7215–7234, Mar. 2025.

[33] B. Cantor, I. T. H. Chang, P. Knight, and A. J. B. Vincent, “Microstructural development in equiatomic multicomponent alloys,” Mater. Sci. Eng. A, vol. 375–377, no. 1-2 SPEC. ISS., pp. 213–218, 2004.

[34] J.-W. Yeh et al., “Nanostructured High-Entropy Alloys with Multiple Principal Elements: Novel Alloy Design Concepts and Outcomes,” Adv. Eng. Mater., vol. 6, no. 5, pp. 299–303, May 2004.

[35] J.-W. Yeh, “Recent Progress in High-entropy Alloys,” Ann. Chim. – Sci. des Mater., vol. 31, pp. 633–648, 2006.

[36] R. Li, L. Xie, W. Y. Wang, P. K. Liaw, and Y. Zhang, “High-Throughput Calculations for High-Entropy Alloys: A Brief Review,” Front. Mater., vol. 7, no. September, pp. 1–12, 2020.

[37] C. Ji et al., “Achieving excellent strength–ductility combination of Al-aided Mg–Gd–Al–Zr–Zn alloys fabricated by cold metal transfer-based wire-arc directed energy deposition via uniform equiaxed grains and multiple precipitates,” Thin-Walled Struct., vol. 201, p. 111980, Aug. 2024.

[38] N. Ali et al., “Enhancing the strength-ductility synergy in hot-forged Fe50Mn30Co10Cr10 high entropy alloy (HEA) through carbon additions,” J. Mater. Res. Technol., vol. 29, no. March, pp. 5646–5655, 2024.

[39] P. K. Ojha, S. Yoshida, U. Sunkari, B. Tripathy, N. Tsuji, and P. P. Bhattacharjee, “Highly deformable Laves phase in a high entropy alloy,” Scr. Mater., vol. 240, no. October 2023, p. 115828, 2024.

[40] P. Cui, W. Wang, Z. Nong, Z. Lai, Y. Liu, and J. Zhu, “Effects of Cr Content on Microstructure and Mechanical Properties of Co-Free FeCryNiAl0.8 High-Entropy Alloys,” Materials (Basel)., vol. 16, no. 9, pp. 1–14, 2023.

[41] Q. Ye et al., “Promoting nanoscale deformation twinning through FCC phase decomposition in AlCoCrFeMo0.05Ni2 high entropy alloy,” J. Alloys Compd., vol. 985, no. March, p. 174086, 2024.

[42] D. Li, P. K. Liaw, L. Xie, Y. Zhang, and W. Wang, “Advanced high-entropy alloys breaking the property limits of current materials,” J. Mater. Sci. Technol., vol. 186, pp. 219–230, 2024.

[43] X. Liu, H. Liu, Y. Wu, M. Li, C. Xing, and Y. He, “Tailoring phase transformation and precipitation features in a Al21Co19.5Fe9.5Ni50 eutectic high-entropy alloy to achieve different strength-ductility combinations,” J. Mater. Sci. Technol., vol. 195, pp. 111–125, 2024.

[44] P. Chakraborty et al., “Design and development of low density, high strength ZrNbAlVTi high entropy alloy for high temperature applications,” Int. J. Refract. Met. Hard Mater., vol. 113, no. February, p. 106222, 2023.

[45] H. Yang, Z. Shao, Q. Lu, C. Cui, L. Xu, and G. Yang, “Development of reduced-activation and radiation-resistant high-entropy alloys for fusion reactor,” Int. J. Refract. Met. Hard Mater., vol. 121, no. December 2023, 2024.

[46] R. Gawel, Ł. Rogal, G. Smoła, and Z. Grzesik, “High-temperature oxidation and diffusion studies on selected Al–Cr–Fe–Ni high-entropy alloys for potential application in thermal barrier coatings,” Intermetallics, vol. 169, no. March, 2024.

[47] F. Golgovici, A. E. Tudose, D. Diniasi, R. Nartita, M. Fulger, and I. Demetrescu, “Aspects of Applied Chemistry Related to Future Goals of Safety and Efficiency in Materials Development for Nuclear Energy,” Molecules, vol. 28, no. 2, p. 874, Jan. 2023.

[48] S. H. Güler, Ö. Güler, E. Kavaz, G. Almisned, B. Issa, and H. O. Tekin, “Exploring critical behavioral differences in physical, structural, and nuclear radiation attenuation properties of produced High Entropy Alloy (HEA) and Refractory-High Entropy Alloy (RHEA) samples,” Curr. Appl. Phys., vol. 58, no. October 2023, pp. 1–10, 2024.

[49] F. Wang, T. Yang, Y. Zhong, L. Li, and T. Yuan, “Design crystallographic ordering in NbTa0.5TiAlx refractory high entropy alloys with strength-plasticity synergy,” J. Mater. Res. Technol., vol. 27, no. December, pp. 8386–8402, 2023.

[50] Z. Q. Xu, Z. L. Ma, M. Wang, Y. W. Chen, Y. D. Tan, and X. W. Cheng, "Design of novel low-density refractory high entropy alloys for high-temperature applications," Mater. Sci. Eng. A, vol. 755, pp. 318–322, May 2019.
[51] O. N. Senkov, D. B. Miracle, and S. I. Rao, "Correlations to improve room temperature ductility of refractory complex concentrated alloys," Mater. Sci. Eng. A, vol. 820, no. May, p. 141512, 2021.
[52] M. A. Tunes, H. T. Vo, J. K. S. Baldwin, T. A. Saleh, S. J. Fensin, and O. El-Atwani, "Perspectives on novel refractory amorphous high-entropy alloys in extreme environments," Appl. Mater. Today, vol. 32, no. February, 2023.
[53] K. Park et al., "Balanced mechanical properties of Al0.5CoCrFeNiTi0.1 high entropy alloy under extreme environments from cryogenic temperature to 800 °C," J. Alloys Compd., vol. 1010, no. December 2024, p. 178199, 2025.
[54] K. Yu et al., "Enhanced wear resistance in (CoCrNi)94Al3Ti3 medium-entropy alloy at high temperatures via nano-Al2O3 reinforcing phase," Tribol. Int., vol. 195, p. 109569, Jul. 2024.
[55] A. Muhammad, Y. Li, D. Bing, A. R. Muhammad, and Z. S. Muhammad, "Excelling mechanical response of a powder metallurgy medium entropy alloy under extreme loading conditions," Powder Technol., vol. 454, no. January, 2025.
[56] W. Chen and X. Li, "Phase stability, microstructure and thermodynamic properties of NbMoZrTiV lightweight high-entropy refractory alloy," J. Mater. Res. Technol., vol. 34, no. December 2024, pp. 2919–2934, 2025.
[57] K. N. Yoon, H. S. Oh, J. Y. Kim, M. S. Kim, J. Zhang, and E. S. Park, "A new class of light-weight metastable high entropy alloy with high strength and large ductility," Materialia, vol. 21, no. November 2021, p. 101284, 2022.
[58] X. Wang et al., "Superior high-temperature strength of a carbide-reinforced high-entropy alloy with ultrafine eutectoid structure," Scr. Mater., vol. 255, no. September 2024, p. 116393, 2025.
[59] P. Kumar, M. O. Jarligo, A. Asad, M. Yakout, and A. McDonald, "Wear and erosion performance of flame sprayed rare earth element-doped AlCoCrFeMo high entropy alloy coatings," Wear, no. January, 2025.
[60] I. Demetrescu, R. Nartita, M. Andrei, A. C. Didilescu, A. Cimpean, and D. Ionita, "Technological Aspects and Performance of High Entropy Alloys with Potential Application in Dental Restorations and Reducing Implant Failure," Appl. Sci., vol. 13, no. 21, p. 12000, Nov. 2023.
[61] C. Vasilescu et al., "Microstructure, Surface Characterization, and Electrochemical Behavior of New Ti-Zr-Ta-Ag Alloy in Simulated Human Electrolyte," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 48, no. 1, pp. 513–523, 2017.
[62] M. Prodana, D. Ionita, A. B. Stoian, I. Demetrescu, G. V. Mihai, and M. Enăchescu, "The Design and Characterization of New Chitosan, Bioglass and ZnO-Based Coatings on Ti-Zr-Ta-Ag," Coatings, vol. 13, no. 3, p. 493, Feb. 2023.
[63] A. B. Stoian, R. Nartita, G. Totea, D. Ionita, and C. Burnei, "Complex Bioactive Chitosan–Bioglass Coatings on a New Advanced TiTaZrAg Medium–High-Entropy Alloy," Coatings, vol. 13, no. 5, p. 971, May 2023.
[64] C. Vasilescu et al., "Microstructure, surface characterization and long-term stability of new quaternary Ti-Zr-Ta-Ag alloy for implant use," Mater. Sci. Eng. C, vol. 71, pp. 322–334, Feb. 2017.
[65] W. Yang, Y. Liu, S. Pang, P. K. Liaw, and T. Zhang, "Bio-corrosion behavior and in vitro biocompatibility of equimolar TiZrHfNbTa high-entropy alloy," Intermetallics, vol. 124, no. June, p. 106845, 2020.
[66] G. Zhang et al., "Dual-structured oxide coatings with enhanced wear and corrosion resistance prepared by plasma electrolytic oxidation on Ti-Nb-Ta-Zr-Hf high-entropy alloy," Surf. Coatings Technol., vol. 456, no. January, p. 129254, 2023.

[67] A. Pantazi et al., “Understanding surface and interface properties of modified Ti50Zr with nanotubes,” Appl. Surf. Sci., vol. 506, p. 144661, Mar. 2020.
[68] A. B. Stoian, I. Demetrescu, and D. Ionita, “Nanotubes and nano pores with chitosan construct on TiZr serving as drug reservoir,” Colloids Surfaces B Biointerfaces, vol. 185, p. 110535, Jan. 2020.
[69] J. E. Berger, A. M. Jorge, G. H. Asato, and V. Roche, “Formation of self-ordered oxide nanotubes layer on the equiatomic TiNbZrHfTa high entropy alloy and bioactivation procedure,” J. Alloys Compd., vol. 865, p. 158837, 2021.
[70] Z. Hua et al., “Development of a Ti49Zr20Hf15Al10Nb6 high entropy shape memory alloy for biomedical applications,” Intermetallics, vol. 180, no. February, p. 108711, 2025.
[71] D. Zhu et al., “Evaluation of wear, corrosion, and biocompatibility of a novel biomedical TiZr-based medium entropy alloy,” J. Mech. Behav. Biomed. Mater., vol. 165, no. February, p. 106951, 2025.
[72] S. Wang et al., “Design of high-ductile medium entropy alloys for dental implants,” Mater. Sci. Eng. C, vol. 113, no. April, p. 110959, 2020.
[73] M. A. Hussein, A. M. Kumar, M. A. Azeem, N. Ankah, and S. Saravanan, “Development of Ti-Zr-Nb-Ta-Ag high entropy alloy for dental implants: In vitro corrosion behavior, antibacterial effect, and surface characteristics,” Mater. Chem. Phys., vol. 329, no. August 2024, p. 130114, 2025.
[74] W. Yang, S. Pang, Y. Liu, Q. Wang, P. K. Liaw, and T. Zhang, “Design and properties of novel Ti–Zr–Hf–Nb–Ta high-entropy alloys for biomedical applications,” Intermetallics, vol. 141, no. November 2021, p. 107421, 2022.
[75] P. Das, C. Sethy, P. M. Pandey, and A. K. Patel, “Evaluation of in vitro degradation behavior and biocompatibility assessment of Mg60Ti24.24Zn9.66Nb6.1 medium entropy alloy,” J. Alloys Compd., vol. 1010, no. December 2024, p. 178003, 2025.
[76] B. Ganesh Reddy Majji, H. Vasudev, and A. Bansal, “Application of plasma-sprayed AlxCrCoFeNi High-Entropy alloys for high-temperature oxidation resistance,” Mater. Lett., vol. 361, no. November 2023, p. 136069, 2024.
[77] H. J. Kwon, K. R. Lim, Y. K. Kim, Y. S. Na, and S. Yi, “Design strategy for high-entropy alloys with enhanced microstructural stability and mechanical properties for high-temperature applications,” Mater. Sci. Eng. A, vol. 889, no. October 2023, p. 145836, 2024.
[78] A. Kumar, M. Abu, N. Krishna, and P. Yadav, “Phase transformation of AB 5 to AB 2 type phase on substitution of Mn with Zr in TiVCoNi (Zr x Mn 2-x) (x = 0 , 0 . 3 , 0 . 6 , 1 . 0) high entropy alloys,” Mater. Chem. Phys., vol. 318, no. March, p. 129291, 2024.
[79] J. Shen, J. Hu, and X. An, “Regulation of phase partition and wear resistance for FeCoCrV high entropy alloy by heat treatment,” Intermetallics, vol. 167, no. December 2023, p. 108232, 2024.
[80] Z. Yang, N. Qiu, H. Yang, and Y. Wang, “Vacancies-mediated atomic diffusion controlled by the interfacial structure of FCC/BCC HEA multilayers,” J. Alloys Compd., vol. 947, p. 169512, 2023.
[81] A. A. Deshmukh and R. Ranganathan, “Recent advances in modelling structure-property correlations in high-entropy alloys,” J. Mater. Sci. Technol., vol. 204, pp. 127–151, 2025.
[82] Y. Yan, X. Hu, Y. Liao, Y. Zhou, W. He, and T. Zhou, “Recent machine learning-driven investigations into high entropy alloys: A comprehensive review,” J. Alloys Compd., vol. 1010, no. September 2024, p. 177823, 2025.
[83] S. H. Guler, A. Yakin, O. Guler, A. K. Chattopadhyay, and T. Simsek, “A critical review of the refractory high-entropy materials: RHEA alloys, composites, ceramics, additively manufactured RHEA alloys,” Curr. Appl. Phys., vol. 70, no. September 2024, pp. 87–124, 2025.

[84] F. Zhang et al., “Recent developments in CoCrFeNi-based high entropy alloy coatings: Design, synthesis, and properties,” J. Alloys Compd., vol. 1018, p. 179193, Mar. 2025.
[85] Z. He et al., “Machine learning guided BCC or FCC phase prediction in high entropy alloys,” J. Mater. Res. Technol., vol. 29, no. December 2023, pp. 3477–3486, 2024.
[86] C. Chen, X. Han, Y. Zhang, P. K. Liaw, and J. Ren, “Phase prediction of high-entropy alloys based on machine learning and an improved information fusion approach,” Comput. Mater. Sci., vol. 239, no. December 2023, p. 112976, 2024.
[87] K. X. Yin, Z. W. Huang, B. L. Wu, G. J. Zhang, Q. W. Tian, and Y. N. Wang, “Prediction of phase stabilities of solid solutions for high entropy alloys,” Acta Mater., vol. 263, no. December 2022, 2024.
[88] Q. Xiang, D. Qi, J. Feng, W. Du, Y. Meng, and F. Zhu, “Unlocking the potential of high entropy alloys in Electrocatalytic reactions: A review,” J. Electroanal. Chem., p. 119083, Mar. 2025.
[89] M. Y. Abdul Salam, E. N. Ogunmuyiwa, V. K. Manisa, A. Yahya, and I. A. Badruddin, “Effect of fabrication techniques of high entropy alloys: A review with integration of machine learning,” Results Eng., vol. 25, p. 104441, Mar. 2025.