

RECENT ADVANCES IN HIGH ENTROPY ALLOYS FOR HIGH-TEMPERATURE STRUCTURAL APPLICATIONS: A REVIEW

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Abstract: The High Entropy Alloys (HEAs), characterized by the presence of multiple principal elements in near-equiatomic proportions, have emerged as a promising class of advanced materials for high-temperature and structural applications. Unlike conventional alloys, HEAs exhibit unique properties such as high strength, excellent thermal stability, superior wear resistance, and enhanced oxidation and corrosion resistance, primarily due to their high configurational entropy, sluggish diffusion, and severe lattice distortion effects. This review presents a comprehensive overview of recent advances in the design, processing, and performance of HEAs, with particular emphasis on their behavior under high-temperature conditions. Key aspects including phase formation, microstructural evolution, mechanical properties, creep resistance, and oxidation behavior are critically discussed. Additionally, various fabrication techniques such as casting, powder metallurgy, and additive manufacturing are examined in relation to their influence on material performance. The challenges associated with HEAs, including cost, scalability, and limited long-term performance data, are also highlighted. Finally, future research directions are proposed, focusing on the development of refractory HEAs, advanced coating systems, and the integration of computational materials science for accelerated alloy design. This review aims to provide valuable insights into the potential of HEAs as next-generation materials for demanding structural and high-temperature applications in aerospace, energy, and automotive sectors..

Keywords: High Entropy Alloys, High Temperature Materials, Structural Applications, Additive Manufacturing

I. INTRODUCTION

High Entropy Alloys (HEAs) represent a significant advancement in materials science, offering a novel approach to alloy design compared to conventional alloys that are typically based on one or two principal elements. HEAs are composed of five or more principal elements in near-equiatomic, leading to high configurational entropy that stabilizes simple solid solution phases such as face-centered cubic (FCC) and body-centered cubic (BCC) structures. The concept of HEAs was first introduced independently by Yeh et al. and Cantor et al. in 2004 [1], [2], marking the beginning of a new paradigm in alloy development.

The unique composition of HEAs results in several fundamental characteristics, commonly referred to as core effects, including the high entropy effect, severe lattice distortion, sluggish diffusion, and the cocktail effect. These effects collectively contribute to enriched mechanical strength, outstanding thermal stability, greater wear resistance, and improved corrosion and oxidation resistance [3]. As a result, HEAs exhibit incomparable performance under extreme conditions, making them attractive for high-temperature and structural applications.

In recent years, widespread research has been conducted to explore the microstructural evolution, mechanical behaviour, and functional properties of HEAs. Advanced processing techniques such as additive manufacturing, powder metallurgy, and arc melting have enabled the development of HEAs with controlled microstructures and tailored properties [4]. Additionally, the emergence of refractory HEAs, lightweight HEAs, and medium entropy alloys has expanded the scope of these materials across multiple engineering domains.

HEAs have confirmed promising potential in various industries, including aerospace, automotive, energy, and defence, where materials are required to withstand high stress, temperature, and corrosive environments. However, challenges such as high production cost, processing complexity, and limited large-scale industrial adoption remain significant barriers to their widespread application.

This review paper aims to provide a comprehensive overview of High Entropy Alloys with a focus on their design principles, mechanical properties, high-temperature performance, and industrial applications. Recent advancements and future research directions are also discussed to highlight the potential of HEAs as next-generation materials for high-performance engineering applications.

1.1 Fundamental Core Effects of High Entropy Alloys

The exclusive properties of High Entropy Alloys (HEAs) are primarily attributed to four fundamental core effects, namely the high entropy effect, severe lattice distortion, sluggish diffusion, and the cocktail effect. These effects distinguish HEAs from conservative alloys and play a crucial role in determining their microstructure, mechanical behaviour, and high-temperature performance.

High entropy effect arises from the presence of multiple principal elements in near-equiatomic proportions, which increases the configurational entropy of the system. This high entropy stabilizes simple solid solution phases such as face-centered cubic (FCC) and body-centered cubic (BCC) structures, while suppressing the formation of complex intermetallic compounds [3]. As a result, HEAs exhibit improved phase stability over a wide range of temperatures. Severe lattice distortion effect is caused by the significant differences in atomic sizes among the constituent elements. This mismatch leads to local lattice strain and distortion, which hinders dislocation movement and enhances the strength of the material. The distorted lattice structure also contributes to improved hardness and wear resistance, making HEAs suitable for structural applications [4].

Sluggish diffusion effect refers to the reduced atomic mobility in HEAs due to the complex atomic environment. The presence of multiple elements with varying bonding characteristics slows down diffusion processes, thereby enhancing high-temperature stability and creep resistance. This effect is particularly beneficial for applications involving prolonged exposure to elevated temperatures [6].

Cocktail effect represents the synergistic interaction of multiple elements, resulting in properties that are superior to those of individual constituent elements. This effect enables HEAs to achieve a unique combination of mechanical strength, ductility, corrosion resistance, and thermal stability. The cocktail effect is often considered a key factor in tailoring the properties of HEAs for specific applications.

Overall, these four core effects collectively contribute to the exceptional performance of High Entropy Alloys. Understanding and optimizing these effects are essential for the design and development of advanced HEAs with enhanced properties for high-temperature and structural applications.

1.2 Classification of High Entropy Alloys

High Entropy Alloys (HEAs) can be broadly classified based on their crystal structure, composition, and functional characteristics. This classification helps in understanding their mechanical behaviour, phase stability, and suitability for specific engineering applications.

One of the primary classifications of HEAs is based on their crystal structure, which includes face-centered cubic (FCC), body-centered cubic (BCC), and mixed-phase (dual-phase) systems. FCC-structured HEAs, such as the well-known CoCrFeMnNi alloy, exhibit excellent ductility, toughness, and good fracture resistance, making them suitable for structural applications requiring high formability [4]. In contrast, BCC-structured HEAs generally demonstrate higher strength and hardness but tend to be relatively brittle at room temperature. These alloys are often preferred for applications where high strength is required, especially at elevated temperatures.

Dual-phase HEAs, which consist of a combination of FCC and BCC phases, offer a balanced combination of strength and ductility. The presence of multiple phases allows for enhanced mechanical performance by utilizing the advantages of

both structures. Such alloys are particularly useful in applications requiring both toughness and high load-bearing capacity.

Another important classification is based on composition, particularly the inclusion of refractory elements. Refractory High Entropy Alloys (RHEAs) are composed of high melting point elements such as molybdenum, niobium, tantalum, and tungsten. These alloys exhibit excellent high-temperature strength, creep resistance, and thermal stability, making them suitable for extreme environments such as aerospace engines and power generation systems [6].

In addition, lightweight High Entropy Alloys (LWHEAs) have been developed to address the need for low-density materials in automotive and aerospace applications. These alloys typically include elements such as aluminium, magnesium, and titanium, which reduce overall density while maintaining acceptable mechanical strength [7].

High Entropy Alloys (HEAs) can also be categorized according to their functional properties, such as magnetic, electrical, and catalytic behavior. Functional HEAs are being explored for applications in energy storage systems, thermoelectric devices, and magnetic materials due to their unique compositional flexibility [10].

Overall, the classification of High Entropy Alloys provides a framework for selecting appropriate alloy systems based on performance requirements. Understanding these categories is essential for designing HEAs tailored to specific high-temperature and structural applications.

1.3 Mechanical Properties of High Entropy Alloys

High Entropy Alloys (HEAs) exhibit a unique combination of mechanical properties that distinguish them from conventional alloys, making them highly suitable for structural and high-temperature applications. These properties are primarily influenced by their multi-element composition, solid solution strengthening, and the presence of the fundamental core effects.

One of the most significant characteristics of HEAs is their high strength and hardness, which arise from severe lattice distortion caused by differences in atomic sizes of constituent elements. This distortion impedes dislocation motion, resulting in enhanced yield strength and hardness [3]. In particular, body-centered cubic (BCC) HEAs demonstrate superior strength, especially at elevated temperatures, although they may exhibit limited ductility at room temperature.

In contrast, face-centered cubic (FCC) HEAs are known for their excellent ductility and toughness. Alloys such as CoCrFeMnNi exhibit remarkable plastic deformation behaviour, even at cryogenic temperatures, due to mechanisms such as dislocation slip and mechanical twinning [4]. This combination of strength and ductility makes FCC HEAs highly attractive for applications requiring both load-bearing capacity and resistance to fracture.

Another important property of HEAs is their enhanced fatigue resistance under cyclic loading conditions. The complex microstructure and uniform distribution of elements contribute to improved resistance to crack initiation and

propagation. This makes HEAs suitable for applications involving repeated stress cycles, such as in aerospace and automotive components.

HEAs also exhibit superior wear resistance due to their high hardness and stable microstructure. The incorporation of multiple principal elements improves resistance to surface degradation, making these alloys well suited for tribological applications, including cutting tools and protective coatings. The deformation mechanisms in HEAs are complex and depend on their crystal structure and composition. These mechanisms include dislocation slip, deformation twinning, and in some cases, phase transformation. Recent studies have shown that short-range ordering within the alloy can significantly influence deformation behaviour and mechanical performance.

Furthermore, HEAs maintain their mechanical properties over a wide temperature range, from cryogenic to elevated temperatures. This thermal stability is a key advantage over conventional alloys, which often experience significant degradation in mechanical performance at high temperatures [6].

In summary, the exceptional mechanical properties of High Entropy Alloys, including high strength, ductility, fatigue resistance, and wear resistance, make them promising candidates for advanced structural applications. Continued research is focused on optimizing these properties through alloy design and processing techniques to meet specific engineering requirements.

II. LITERATURE REVIEW

The concept of High Entropy Alloys (HEAs) was first introduced by J. W. Yeh et al. [1] and Brian Cantor et al. [2] in 2004, marking a significant shift from conventional alloy design based on one or two principal elements to multi-component systems with near-equiatomic compositions. Their pioneering work demonstrated that such alloys could form simple solid solution phases rather than complex intermetallic compounds, thereby opening new directions in materials science.

Subsequent studies have focused on understanding the fundamental principles governing HEAs. Daniel B. Miracle and Senkov [3] provided a comprehensive review of HEA systems, emphasizing the importance of configurational entropy and the four core effects—high entropy effect, lattice distortion, sluggish diffusion, and cocktail effect—in determining alloy behaviour. Similarly, Edwin P. George et al. [4] highlighted the exceptional mechanical properties of HEAs, particularly their unique combination of strength and ductility, which is uncommon in traditional alloys.

Research has also been directed toward understanding the microstructure and mechanical performance of HEAs. Zhang et al. [5] presented a detailed study on the microstructures and properties of HEAs, while Otto et al. [14] investigated the influence of temperature and microstructure on the tensile behaviour of CoCrFeMnNi alloys. Additionally, Gali and George [7] examined tensile properties of both high- and medium-entropy alloys, demonstrating their potential for structural applications.

Significant progress has been made in the development of refractory High Entropy Alloys (RHEAs), which are designed for high-temperature applications. Senkov et al. [6], [13] reported excellent mechanical properties and thermal stability in refractory systems such as Nb–Mo–Ta–W-based alloys, making them promising candidates for aerospace and energy applications.

Advancements in processing techniques have further enhanced HEA development. Powder metallurgy and additive manufacturing methods have enabled improved control over microstructure and composition. Fu et al. [15] demonstrated the fabrication of HEAs using powder metallurgy, while recent studies highlight the growing importance of additive manufacturing techniques such as Selective Laser Melting for producing complex HEA components with refined microstructures.

In addition, alloy design strategies have been significantly improved through the use of empirical and computational approaches. Guo et al. [16] explored the effect of valence electron concentration on phase stability, while modern approaches incorporating machine learning and computational thermodynamics have accelerated the discovery and optimization of HEAs [11].

More recently, HEAs have been explored for functional and advanced applications beyond structural use. Zou et al. [17] reported ultra-strong and ductile HEAs at small scales, while Shi et al. [10] reviewed corrosion-resistant HEAs for harsh environments. These studies highlight the versatility of HEAs across multiple domains, including energy, electronics, and catalysis.

Despite these advancements, challenges such as high production cost, limited scalability, and incomplete understanding of long-term performance persist. Therefore, continued research is essential to address these limitations and to fully realize the potential of HEAs in next-generation engineering applications.

III. METHODOLOGY

The design of High Entropy Alloys (HEAs) is fundamentally different from conventional alloy systems and requires a systematic approach to achieve the desired combination of microstructure and properties. Various alloy design strategies have been developed based on thermodynamic, empirical, and computational methods to control phase formation, stability, and mechanical performance.

One of the key strategies in HEA design relies on thermodynamic concepts, particularly configurational entropy and phase stability criteria. Factors such as atomic size mismatch, mixing enthalpy, and valence electron concentration (VEC) are commonly employed to predict the formation of solid solution phases. For example, alloys with higher VEC values generally tend to form face-centered cubic (FCC) structures, while lower VEC values favor body-centered cubic (BCC) structures. Additionally, the application of CALPHAD (Calculation of Phase Diagrams) methods has significantly improved the ability to predict phase equilibria and microstructural evolution in complex HEA systems.

Another important strategy involves composition-based design, where the selection and proportion of constituent elements are tailored to achieve specific

properties. Elements such as aluminium and titanium are incorporated to reduce density and improve strength, while refractory elements like molybdenum, niobium, tantalum, and tungsten are added to enhance high-temperature performance. This approach allows the development of specialized HEAs, including lightweight HEAs and refractory HEAs, for targeted applications [6].

In recent years, computational and machine learning-based design methods have emerged as powerful tools for accelerating HEA development. These methods utilize large datasets and predictive algorithms to identify optimal compositions, predict phase stability, and estimate mechanical properties with high accuracy [9]. Machine learning models significantly reduce the need for extensive experimental trials and enable rapid screening of potential alloy systems.

Additionally, processing-driven design strategies play a crucial role in tailoring HEA properties. Techniques such as additive manufacturing, powder metallurgy, and thermo-mechanical processing can influence grain size, phase distribution, and defect structure, thereby affecting the overall performance of the alloy. Control over processing parameters allows for the optimization of microstructure and enhancement of mechanical properties.

Furthermore, the concept of multi-objective optimization is gaining importance in HEA design, where multiple properties such as strength, ductility, corrosion resistance, and thermal stability are simultaneously considered. This holistic approach ensures the development of balanced alloys suitable for complex engineering applications.

In summary, alloy design strategies for HEAs involve a combination of thermodynamic modelling, compositional tuning, advanced computational methods, and processing techniques. These integrated approaches are essential for developing next-generation HEAs with superior performance for high-temperature and structural applications.

Manufacturing Techniques of High Entropy Alloys The fabrication of High Entropy Alloys (HEAs) plays a critical role in determining their microstructure and overall performance. Due to their multi-element composition and complex phase behaviour, both conventional and advanced manufacturing techniques are employed to produce HEAs with desired properties.

3.1 Conventional Processing Methods

Conventional processing techniques such as arc melting and vacuum induction melting are commonly employed for synthesizing HEAs. In arc melting, high-purity elemental components are melted in an inert atmosphere to maintain chemical uniformity and minimize contamination, often requiring multiple remelting cycles to achieve a homogeneous composition. Likewise, vacuum induction melting offers enhanced control over alloy composition while limiting oxidation during processing.

Another widely used approach is powder metallurgy, which involves blending elemental or pre-alloyed powders followed by compaction and sintering. This technique provides better compositional control, minimizes segregation, and enables the production of fine-grained microstructures. It is especially advantageous for fabricating HEAs with complex compositions and tailored properties.

3.2 Additive Manufacturing Techniques

In recent years, additive manufacturing (AM) has emerged as a promising approach for producing HEAs with complex geometries and controlled microstructures. Techniques such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) enable layer-by-layer fabrication of components directly from digital models. These methods allow precise control over process parameters, resulting in refined microstructures and enhanced mechanical properties [8].

Additive manufacturing also reduces material wastage and enables the production of intricate components that are difficult to achieve using conventional methods. However, challenges such as residual stresses, porosity, anisotropy, and microstructural inhomogeneity need to be addressed to ensure consistent performance of additively manufactured HEAs.

3.3 Thermo-Mechanical Processing

Post-processing techniques such as hot rolling, forging, and annealing are often employed to further refine the microstructure and improve mechanical properties. These processes help in reducing defects, enhancing grain structure, and improving ductility and strength.

3.4 Emerging Processing Techniques

Advanced techniques such as spark plasma sintering (SPS) and mechanical alloying are gaining attention for HEA fabrication. Mechanical alloying involves high-energy ball milling of elemental powders, leading to the formation of homogeneous alloy compositions at the atomic level. Spark plasma sintering enables rapid densification at lower temperatures, preserving fine microstructures and enhancing material properties.

IV. APPLICATIONS OF HIGH ENTROPY ALLOYS

a) High Entropy Alloys (HEAs) have emerged as promising materials for a wide range of engineering applications due to their superior mechanical properties, excellent thermal stability, and resistance to wear, corrosion, and oxidation. Their unique multi-element composition enables them to perform efficiently under extreme operating conditions, making them suitable for advanced industrial applications.

b) In the aerospace sector, HEAs are extensively investigated for use in high-temperature components such as turbine blades, jet engine parts, and thermal protection systems. Refractory High Entropy Alloys (RHEAs), which contain high melting point elements such as molybdenum, niobium, tantalum, and tungsten, exhibit exceptional strength and creep resistance at elevated temperatures, making them ideal for next-generation aerospace structures.

c) In the automotive industry, HEAs are utilized in components that require high wear resistance and thermal durability, including engine parts, exhaust systems, and braking components. The development of lightweight HEAs has further enhanced their applicability by improving fuel efficiency and reducing overall vehicle weight.

d) HEAs also play a crucial role in the energy sector, particularly in nuclear reactors, gas turbines, and hydrogen storage systems. Their excellent radiation resistance, corrosion resistance, and thermal stability make them suitable for long-term operation in harsh environments. Additionally, their

potential use in renewable energy systems and energy storage devices is gaining increasing attention.

e) In the field of surface engineering, HEAs are widely used as protective coatings due to their high hardness and resistance to wear and corrosion. Applications include thermal barrier coatings, cutting tool coatings, and marine protective layers. These coatings significantly enhance the service life of components operating under severe conditions.

f) Biomedical applications of HEAs are also emerging, particularly in the development of orthopaedic implants, dental materials, and surgical instruments. Their biocompatibility, corrosion resistance, and mechanical strength make them suitable for medical use, although further research is required to ensure long-term safety and performance.

g) Moreover, HEAs are being explored for functional applications in electronics and energy devices due to their unique electrical, magnetic, and catalytic properties. They are used in thermoelectric materials, soft magnetic components, and catalysts for fuel cells and batteries. In defence and space applications, HEAs are utilized in armor materials, missile components, and spacecraft structures due to their ability to withstand extreme stress and temperature conditions.

h) Global, the versatility and superior performance of High Entropy Alloys make them highly attractive for a broad spectrum of applications across multiple industries, positioning them as key materials for future technological advancements.

V. CHALLENGES IN HIGH ENTROPY ALLOYS

Despite the significant advancements and promising properties of High Entropy Alloys (HEAs), several challenges must be addressed before their widespread industrial adoption. These challenges are primarily related to material cost, processing complexity, limited understanding of long-term behaviour, and scalability of production.

A key limitation of HEAs is their high material cost, as they frequently incorporate multiple high-purity and expensive elements such as cobalt, nickel, tantalum, and tungsten. This significantly increases production expenses, limiting their economic feasibility for large-scale applications.

Another major challenge lies in processing and fabrication. Owing to their multi-component nature, achieving a uniform composition and preventing segregation during solidification is difficult. Although advanced techniques like additive manufacturing show great potential, they can introduce issues such as residual stresses, porosity, and anisotropy, which may adversely affect mechanical performance.

Additionally, the long-term performance of HEAs remains insufficiently understood. While these alloys exhibit excellent mechanical and thermal properties under laboratory conditions, their behaviour under prolonged exposure to extreme environments—such as high temperatures, radiation, and cyclic

loading—requires further study. In particular, aspects like creep behaviour and phase stability over extended service periods need more detailed investigation.

Additionally, difficulty in predicting phase formation poses a significant challenge in HEA design. The presence of multiple elements leads to complex interactions, making it challenging to accurately predict whether the alloy will form a stable solid solution or undesirable intermetallic phases. While computational tools and machine learning approaches are being developed, reliable predictive models are still under refinement [9].

Another important issue is the lack of standardization and industrial guidelines. There are currently no universally accepted standards for the classification, testing, and certification of HEAs, which hinders their acceptance in critical industries such as aerospace and nuclear sectors.

Furthermore, scalability of production remains a major challenge. Most HEAs are currently produced at laboratory scale, and transitioning to large-scale industrial manufacturing requires significant advancements in processing techniques, cost reduction, and quality control.

VI. FUTURE DEVELOPMENT

High Entropy Alloys (HEAs) present significant future potential for advanced engineering applications, particularly through the integration of artificial intelligence and machine learning for accelerated alloy design and optimization of phase stability, mechanical properties, and performance. Future research is likely to emphasize the development of lightweight HEAs by incorporating low-density elements such as aluminum, magnesium, and titanium, thereby expanding their suitability for aerospace and automotive applications. Enhancing high-temperature performance—particularly creep resistance and oxidation stability above 1000°C—remains a key focus area, especially for refractory HEAs. In addition, additive manufacturing methods like Selective Laser Melting are expected to play a significant role in HEA fabrication; however, challenges related to residual stresses, porosity, and precise microstructural control still need to be effectively addressed. Moreover, HEAs are gaining attention in surface engineering, especially for applications such as thermal barrier and wear-resistant coatings. An emerging trend involves the design of multifunctional HEAs that combine mechanical, electrical, and thermal capabilities. In parallel, efforts aimed at reducing costs, utilizing recycled resources, and developing scalable manufacturing techniques are vital for their successful commercialization. In addition, expanding applications in energy systems, hydrogen storage, nuclear materials, and space technologies highlights the broad future scope of HEAs. Overall, continued advancements in design, processing, and characterization are expected to establish HEAs as a key class of materials for next-generation high-temperature and structural applications.

VI. CONCLUSION

High Entropy Alloys (HEAs) represent a paradigm shift in materials engineering, offering an exceptional combination of mechanical strength, thermal stability, corrosion resistance, and wear resistance due to their multi-principal

element composition and associated core effects. This review has outlined the fundamental concepts, alloy design approaches, classification, mechanical properties, high-temperature performance, processing methods, and a wide range of applications of HEAs. Recent developments—particularly in refractory and lightweight HEAs, along with the adoption of additive manufacturing and machine learning—have further broadened their potential for high-temperature and structural applications.

However, several challenges continue to limit their large-scale industrial adoption. High material costs, complexities in processing, insufficient long-term performance data, and the absence of standardized guidelines remain key concerns. Overcoming these issues through optimized alloy design, advanced manufacturing techniques, and comprehensive performance assessment will be crucial for their practical implementation.

In conclusion, HEAs show significant promise as next-generation materials for demanding engineering applications, especially in aerospace, automotive, and energy sectors. Ongoing research and technological progress are expected to enhance their performance and support their transition from laboratory research to widespread industrial deployment.

REFERENCES

- [1]. J. W. Yeh, S. K. Chen, S. J. Lin, J. Y. Gan, T. S. Chin, T.
- [2]. T. Shun, C. H. Tsau, and S. Y. Chang, "Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes," *Advanced Engineering Materials*, vol. 6, no. 5, pp. 299–303, 2004.
- [3]. B. Cantor, I. T. H. Chang, P. Knight, and A. J. B. Vincent, "Microstructural development in equiatomic multicomponent alloys," *Materials Science and Engineering A*, vol. 375–377, pp. 213–218, 2004.
- [4]. D. B. Miracle and O. N. Senkov, "A critical review of high entropy alloys and related concepts," *Acta Materialia*, vol. 122, pp. 448–511, 2017.
- [5]. E. P. George, D. Raabe, and R. O. Ritchie, "High-entropy alloys," *Nature Reviews Materials*, vol. 4, pp. 515–534, 2019.
- [6]. Y. Zhang, T. T. Zuo, Z. Tang, M. C. Gao, K. A. Dahmen,
- [7]. P. K. Liaw, and Z. P. Lu, "Microstructures and properties of high-entropy alloys," *Progress in Materials Science*, vol. 61, pp. 1–93, 2014.
- [8]. O. N. Senkov, G. B. Wilks, J. M. Scott, and D. B. Miracle, "Mechanical properties of Nb₂₅Mo₂₅Ta₂₅W₂₅ and V₂₀Nb₂₀Mo₂₀Ta₂₀W₂₀ refractory high entropy alloys," *Intermetallics*, vol. 19, no. 5, pp. 698–706, 2011.
- [9]. A. Gali and E. P. George, "Tensile properties of high- and medium-entropy alloys," *Intermetallics*, vol. 39, pp. 74–78, 2013.
- [10]. B. Gludovatz, A. Hohenwarter, D. Catoor, E. H. Chang, E.
- [11]. P. George, and R. O. Ritchie, "A fracture-resistant high-entropy alloy for cryogenic applications," *Science*, vol. 345, no. 6201, pp. 1153–1158, 2014.

- [12]. Z. Li, K. G. Pradeep, Y. Deng, D. Raabe, and C. C. Tasan, "Metastable high-entropy dual-phase alloys overcome the strength-ductility trade-off," *Nature*, vol. 534, pp. 227–230, 2016.
- [13]. Y. Shi, B. Yang, and P. K. Liaw, "Corrosion-resistant high-entropy alloys: A review," *Metals*, vol. 7, no. 2, p. 43, 2017.
- [14]. M. C. Gao, J. W. Yeh, P. K. Liaw, and Y. Zhang, *High-Entropy Alloys: Fundamentals and Applications*. Cham, Switzerland: Springer, 2016.
- [15]. D. B. Miracle, "High-entropy alloys: A current evaluation of founding ideas and core effects and exploring 'nonlinear alloys'," *JOM*, vol. 69, no. 12, pp. 2130–2136, 2017.
- [16]. O. N. Senkov, J. M. Scott, S. V. Senkova, D. B. Miracle, and C. F. Woodward, "Microstructure and room temperature properties of a high-entropy TaNbHfZrTi alloy," *Journal of Alloys and Compounds*, vol. 509, no. 20, pp. 6043–6048, 2011.
- [17]. F. Otto, A. Dlouhý, K. G. Pradeep, M. Kuběnová, D. Raabe, and E. P. George, "The influences of temperature and microstructure on the tensile properties of a CoCrFeMnNi high-entropy alloy," *Acta Materialia*, vol. 61, no. 15, pp. 5743–5755, 2013.
- [18]. Z. Fu, W. Chen, H. Wen, E. J. Lavernia, and J. M. Schoenung, "Microstructure and mechanical properties of CoCrFeMnNi high-entropy alloy fabricated by powder metallurgy," *Materials Science and Engineering A*, vol. 644, pp. 10–16, 2015.