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High-Entropy Alloys: Advantages and Applications in Challenging Environments

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ABSTRACT

Modern mechanical applications demand robust materials with boosted mechanical properties capable of resisting challenging working conditions. Single substances and pure material might fail to meet all application requirements translated by larger robustness and endurance. Correspondingly, scholars developed functional substances recognized with high-energy alloys (HEAs) with upgraded strength, durability, and corrosion behavior. Nonetheless, the available literature requires further research that provides sufficient insights pertaining to HEAs' contributions. Consequently, this research is guided, aiming to bridge this knowledge gap by exploring the contributory merits and valuable benefits of HEAs when engaged in challenging operating circumstances. The article addresses the promising HEA gains, their leading features, relevant properties, and diversified applications. The method adopted in this work comprises a scoping review through which multiple peer-reviewed articles and recent publications (2003 to 2023) were surveyed, addressing contributory gains of HEAs in fulfilling enhanced mechanical performance for different applications. Based on the scoping overview led in this paper, it was found that HEAs could serve in multiple engineering areas under challenging working conditions owing to their practical properties, namely elevated hardness, augmented mechanical strength, amended fatigue resistance, elaborated ductility, optimal toughness, superior microstructure stability at high temperatures, and exceptional wear resistance, considerable corrosion resistance, and boosted oxidation resilience. Accordingly, these excellent characteristics enable their broad implementation in vital engineering disciplines and arduous practices, notably aviation, automotive, maritime, energy storage systems (ESSs), and additive manufacturing. Additionally, the review outcomes revealed that mixing multiple elements together with numerous crystal structures could provide significant strength-to-weight ratios, helping exhibit various potent features compared with traditional alloys. In light of this framework, the implications of this research are mirrored by focusing more attention on the consequential engineering influences and feasible practicalities of HEAs to promote their extensive utilization in multiple domains, allowing supportive qualities and advantageous effects on entire material characteristics to each application they are engaged in. From this perspective, it is suggested to manage additional research processes to classify vital gains of HEAs and elucidate their added value.

1. INTRODUCTION

HEAs can be described as alloys that result from a mix of multiple elements. This mixture could offer a novel material with significantly enhanced mechanical properties and physical characteristics compared to the original materials [1-4]. HEAs exhibit remarkable enhancements in their mechanical and physical features, including oxidation, corrosion resistance, tensile strength, fracture resistance, and strength-to-weight ratios [5-7]. Figure 1 illustrates the classification of HEAs with other materials in terms of length scale and structural and chemical complexity.

As Figure 1 indicates, HEAs are characterized by their small length (which lies between 1 μm and 100 μm). Furthermore, they are located between binary compounds and quasicrystals in terms of their structural complexity.

This multiple mix of crystal materials could attain amended mechanical characteristics of the new alloys can be obtained. HEAs can allow new metal alloys to achieve better profitability and cost-effectiveness in numerous applications [8, 9].

It is noted that, however, there is little background and detailed discussion of HEA's contributory benefits and valuable attributes. Accordingly, there is a pressing need to explore how HEAs could serve in varied applications based on their augmented features. On the grounds of this background, the critical goal of this research is to examine various valuable mechanical, electrical, and magnetic properties, besides other HEA functional features.

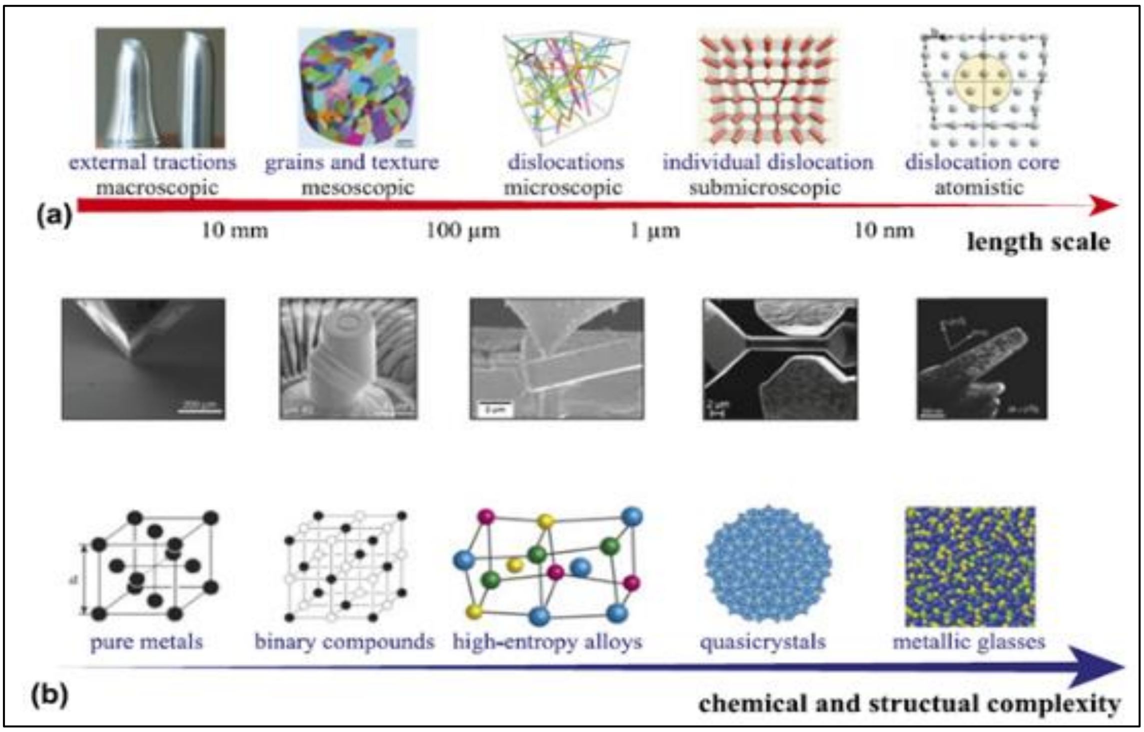

Figure 1. The classification of HEAs with other materials in terms of length scale and structural and chemical complexity level [10]

1.1 HEA evolution and corresponding useful features

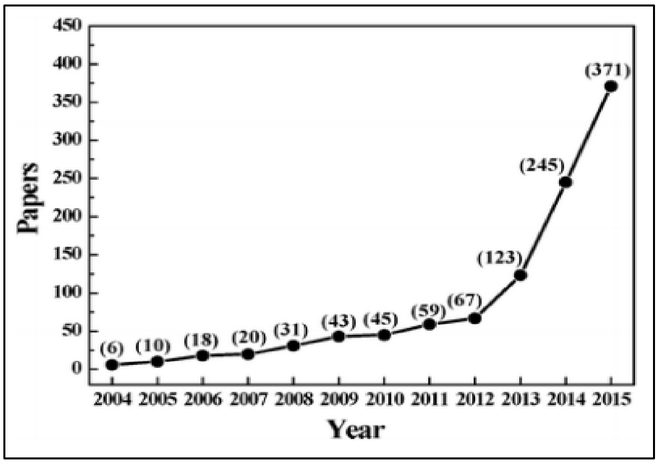

Figure 2. Number of HEA system-related articles published up until 2015 [11]

HEAs have recently been added as a new branch to the metallic alloy tree. They can be featured as alloy systems involving five or more primary alloying components or have a mixture entropy higher than 1.5R [11]. Despite the initial appearance that they could produce extremely complex microstructures with multiple phases, intermetallic compounds, and segregations, making them difficult to understand and analyze, these innovative materials have typically simple crystal structures like face-centered cubic (FCC) and body-centered cubic (BCC) due to the thermodynamics applied to a multi-component system. The first information in 2004 saw the publication of high entropy crystalline alloys—roughly 19 years ago [12]. Since ancient times, most alloy design has only been adding minor elements to alter the properties of a primary metal element, such as aluminum, copper, ferrous, magnesium, or titanium. HEAs were developed in 1995 utilizing an innovative alloy design idea [13]. This area of study was examined using early theories. However, these alloys had complex microstructures and uninteresting characteristics in different circumstances [14]. Publications on HEAs have increased globally after various intriguing features were noticed globally in the initial research, as shown in Figure 2.

A 2003 research published in the HEA field is relevant even if it doesn't provide any results since it teaches important HEA ideas beautifully and emotionally [12]. It was not until Yeh et al. [15] and Candor et al. [16] separately began researching multiple-element alloys in 2004.

HEA systems, such as Al-Co-Cr-Cu-Fe-Ni, Co-Cr-Cu-Fe-Ni-Ti, Al-Co-Cr-Cu-Fe-Ni-B, Al-Co-C, and Al-Co-Cr-Cu-Fe-Ni-V offer excellent characteristics such as high hardness and strength, excellent wear resistance, high-temperature strength, good structural stability, limited diffusion, oxidation resistance over conventional alloys since [17] first discovered them. Afterwards, HEAs became an essential topic in material science. In several technical industries, including aerospace, energy, transportation, and manufacturing, advanced levels of potency, robustness, efficiency, and durability have been demanded in materials. To fulfil the increasing needs posed by operating circumstances in these high-end applications, new materials have been investigated. Traditional commercial alloys are capable of performing these tasks, but they have drawbacks such as low specific weight and high density, which have an adverse effect on structural applications [11]. These characteristics contribute to significant benefits in a broad range of applications. Recently, there has been a lot of interest in HEAs. A new frontier in metallic materials has been formed by developing more than 300 HEAs so far. The connections between phase, microstructure, and mechanical characteristics are the subject of most HEA investigations. Although HEAs' physical characteristics received less attention, they are highly promising. For instance, the study [18] provided a brief evaluation of current knowledge about the mechanical, thermal, and physical attributes of HEAs. Iron is the primary component of steel alloys, whereas nickel and cobalt are the primary components of superalloys. According to the initial definition given to HEAs, these substances represent a novel type of metallic systems that contain at least five distinct principle elements. The term "principal elements" refers to materials that account for at least 5% of the content of an alloy. The ratios between the primary components are mole ratios or very near to them, and the content of the main element's ranges from 5% to 35%, while that of the minor components is less than 5% [19]. Their projected level of mixing entropy was utilized as the basis for the second notation adopted to describe their conception. The concept of HEAs has also been referred to as the entropy of mixing.

Any alloy with a configurational entropy value higher than 1.5R qualifies as a HEA by this criterion [11]. The multiple HEA categories have led to some misunderstanding, which urged discussions respecting which alloys are within the HEA umbrella. In one of the early papers, HEAs are predominantly depicted as "those comprising of five or more primary elements in equimolar ratios" according to a composition-based definition. HEAs can also include small elements to modify the characteristics of the original HEA and produce more HEAs. The amount of entropy is not constrained by this composition-based approach, which gives elemental concentrations. Therefore, this idea does not need the existence of a single-phase SS [12].

The term "high entropy" serves as a catalyst for a definition based on the quantity of entropy. The distinction between alloys with low, medium, and high entropy is thus made using a separate concept. The Boltzmann equation provides an easy way to describe solid solution strengthening (SSS), ideal from alloy composition, nevertheless necessitates that atoms occupy arbitrary lattice locations. This idea also suggests an alloy's configurational entropy has a fixed value. The entropy of an alloy can, nevertheless, vary with temperature. The effects of temperature can be minor, like a very slight change in the short-range atomic ordering, or they can be large, like chemically separating the product and parent phases during a first-order phase shift. The entropy-based concept makes the assumption that the alloy may be characterized by "liquid solution and high temperature solid solution states where the thermal energy is substantial enough to cause separate elements to have random positions within the structure" to address these problems. This aspect indicates that such a scenario is only possible at extremely high temperatures or when the alloy is liquid and characterizes an alloy using its most outstanding level of entropy. At the melting temperature, the atomic positions in binary metallic liquids are not necessarily random. This feature is consistent with earlier research that suggested metallic treatments are frequently not the best option. These issues make it challenging to apply this definition. Commercially available alloy systems are based on either aluminum, nickel, iron, or copper in the case of superalloys.

Nonetheless, the variety of alloys that can be made using these traditional alloy processes is limited. New alloys called "high entropy alloys" were developed at the beginning of the millennium. These alloys were made using equiatomic substitution, which entails substituting near-equiatomic or multi-component equiatomicmixes of chemically similar species for individual components. The behavior of binary systems is well understood, yet little is known pertaining to these systems themselves. This paper looks at the development of HEAs, their characteristics, and their present and future applications.

A quarter of the mass of the Earth is made up of metals, which make up around two-thirds of all the elements. Because they seldom exibit a favorable mix of qualities for thermal, structural, and other mechanical purposes, metals are rarely employed in their pure form. By adding other elements to the pure metal, this property restriction is removed. Solute addition to a single base is the foundation of conventional alloys. The selection of one or two critical elements in created alloys is dependent on the qualities needed for the alloy's purpose. Excellent strength alloys with high thermal stability at elevated temperatures are frequently required [20].

2. HEA'S FOUR CORE EFFECTS

Owing to each component's equimolar concentration, HEA compositions are more complicated than those of ordinary alloys. HEAs have various distinct kinetic and thermodynamic features because of the revolutionary alloy design idea and high-concentration solid solution structure which enables the development of distinctive and functional properties [21]. According to the studies [11, 22, 23], the four core effects of HEAs can be summarized by the following aspects:

(1) High-entropy processes known as hermodynamics allow a material to form simpler solid solution phases, frequently FCC and BCC.
(2) The kinetics of microstructural level processes, including creep, grain development, and recrystallization are reduced by slow diffusion.
(3) Severe lattice distortion enhances the chemical and mechanical characteristics of structures.
(4) The interaction between the various elements improves the alloy's characteristics in comparison to those that would be predicted from the law of mixes, which is how cocktail effects may be described on an atomic scale.

The specifics of each consequence will be covered. The four main impacts and their connection to microstructure and characteristics are summarized in Figure 3 [14].

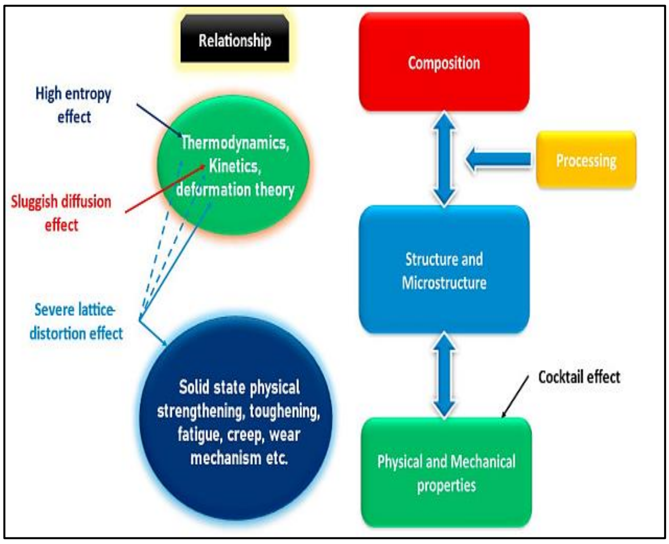

Figure 3. Four core effects and their relationships [14]

2.1 High entropy effect

Basic structures like FCC and BCC have a lower Gibbs energy when all the components are present because there is a high number of unique elements in the mixture, which leads to a high mixing entropy. More solution phases arise in this way under conditions of high entropy. These high entropy phases are stabilized by this Gibbs energy reduction, leading to a simple microstructure [11]. According to the studies [24, 25], the high configurational entropy impact promotes the creation of solid solutions while impeding phase transformations that would otherwise affect the system's thermodynamics [26].

Different binary to septenary alloys' XRD patterns are displayed in Figure 4. The concept that both ternary and binary compounds would evolve defies such primary structural forms [27].

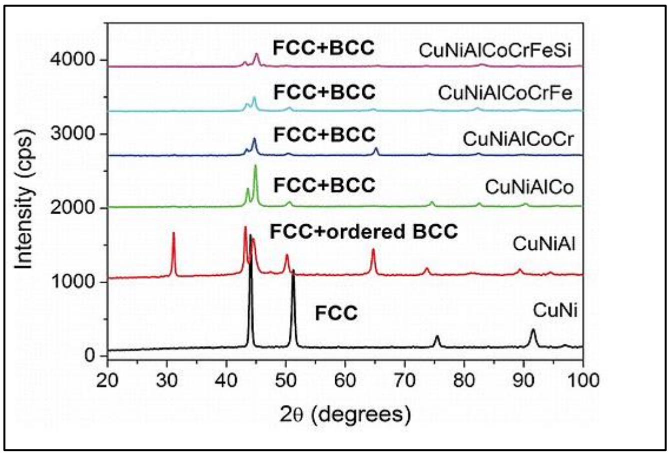

Figure 4. The XRD patterns of an alloy produced by sequentially adding an extra element to the one before [27]

The only two essential phases of senary, septenary, and quinary alloys are BCC and FCC, which have simplified structures. This aspect indicates that these alloys' phases remain pretty simple (note that the septenary alloy basically contains phases of minor intermetallic, although unclear in the XRD pattern).

2.2 Sluggish diffusion effect

Sluggish diffusion affects the system's kinetics; it positively affects thermal stability, recrystallization temperature, grain development, phase separation, and creep resistance, which may be advantageous to the microstructure [28]. The diffusion process may become slow, and the system's temperature may drop if the number of elements in alloy increases [24, 29].

2.3 Severe lattice distortion

Because of the significant entropy influence, HEAs consist of a single matrix, whether an FCC, BCC, or other structure. As a result, each component joins the whole. The resulting solid solution's lattice is severely deformed since each element has a unique atomic size, bonding energy with other elements, and inclination toward crystal formation. Lattice distortion affects the final properties of the alloys, such as their hardness and tensile strength, because it inhibits dislocations from freely migrating as expected [30, 31]. Another significant result is that the features' dependence on temperature is reduced [11, 24]. Mismatch in shear modulus between the atoms' constituents, which leads to hardening, and the electronic structures linked to variations in local bond states, for example, may have an impact on thermal and electrical conductivities [12, 32, 33].

2.4 The 'cocktail' effect

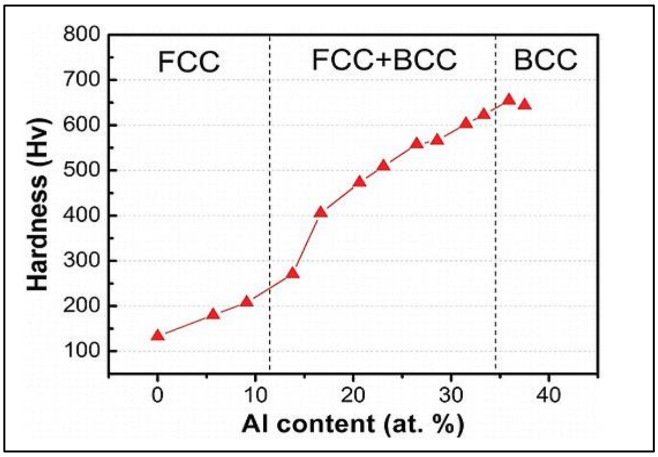

Figure 5. Hardness of the $Al_xCoCrCuFeNi$ alloys as a function of Al content [27]

HEAs can be viewed as a composite on an atomic level. This feature confirms that interactions between different components produce properties other than those expected by the rule of mixtures. Additional impacts of the cocktail effect include hardening the system and encouraging the production of a particular phase, like aluminum, which can produce either FCC or BCC structures depending on its concentration [11, 34]. The "cocktail" effect takes into account the powerful structural and functional capabilities of "gum" metals as well as the remarkably distinctive qualities of totally amorphous bulk metallic glasses [12, 35, 36]. The "cocktail" effect serves as a warning to be open-minded to non-linear, unexpected consequences that may follow from odd assemblages of components and microstructures in the ample composition space of multi-principal element alloys MPEAs [12].

Figure 5 describes the hardness of the $Al_xCoCrCuFeNi$ alloy as a function of Al concentration. It is evident that adding Al could make the alloy significantly more challenging. Al's larger atomic size, the emergence of a complex BCC phase, and more cohesive bonding with other elements are all contributing factors. Hence, the macroscopic characteristics of HEA include the averaged properties of the component elements and the effects of the surplus quantities caused by inter-elemental reactions and lattice distortion [27].

3. HIGH ENTROPY ALLOY PROPERTIES

Tying together composition, microstructure, and property data provides new challenges in the research of HEAs. The quantity of alloys which must be significantly defined grows due to the wide range of compositions. In light of the fact that components are usually more localized in HEAs than in traditional alloys, regardless of the same alloy family, changing just one element can considerably impact microstructure and characteristics. Accordingly, the following section will examine HEA's physical (electrical and magnetic), mechanical, and thermal properties.

3.1 Electrical properties

For the same composition, the FCC phase has a larger electrical resistivity than the BCC phase, and the linear average of the volume fractions of the BCC and FCC phases determines the electrical resistivity in a two-phase field. For instance, the usual range of electrical resistivity for $Al_xCoCrFeNi$ alloys (0 × 2) is 100-200 cm. The electrical resistance of each of these alloys rises with a linear trend with temperature. A non-monotonic electrical resistivity dependence could result from the microstructures switching from "FCC" to "BCC" as the Al content rises. Electrical resistivity is predicted to rely monotonically no longer on Al concentration with the switch from BCC to FCC microstructures. Cold-rolled Comparing homogenized materials to cold-rolled alloys, resistance is increased [37-39].

3.2 Magnetic properties

To prevent materials from being strained by an external magnetic field, the magnetostriction effect must be very modest. Relying on the number of current magnetic components, HEA's magnetic characteristics could be modified. Processing and thermal history have an impact on magnetic characteristics through the phases that are created. Compared to annealed materials, as-processed materials frequently have unique microstructures and magnetic characteristics [12, 40].

Investigations on the magnetic characteristics of HEAs have mainly concentrated on alloys made of Cr, Co, Al, Cu, Ni, Ti, and Fe. Higher magnetization often represents the result of having more magnetic elements. However, adding components to alloys can have a considerable influence. For instance, magnetization is decreased when Cr is added. The conclusion reached by Zhang et al. [26] that the presence of Cr causes the cancellation of magnetization appears to be supported by the observation that the separation of Cr from Fe and Co results in increased magnetization. Like conventional magnetic materials, higher coercivities are associated with finer microstructures [41].

3.3 Thermal properties

Thermal conductivity, K (T), is frequently determined by measuring a material's density, specific heat, and thermal diffusion coefficient (T). The region with the lowest thermal conductivity is the FCC + BCC duplex [22]. Low Al concentration single-phase FCC alloys have a thermal conductivity almost half that of high Al content (single-phase BCC alloys). As Al concentration rises in single-phase zones, the thermal conductivity falls. Lattice distortions and an improved phonon mean free path brought on by lattice thermal expansion at elevated temperatures are thought to be the causes of these events [42, 43].

3.4 Mechanical properties

Composition and microstructure have a significant impact on mechanical characteristics. While flaws are essential microstructural elements that substantially affect mechanical properties, the composition determines elastic characteristics and atomic interactions that determine dislocation behaviors [12, 44].

3.4.1 Hardness

Other factors should be considered to understand this wide range of hardness ratings. Whether the sample was produced utilizing liquid-state or solid-state processing will impact the manufacturing procedure [45, 46].

The hardness of an alloy depends on its constituent parts, how they interact with one another and other properties. Figure 6 depicts that most HEAs have harder surfaces than standard alloys [47].

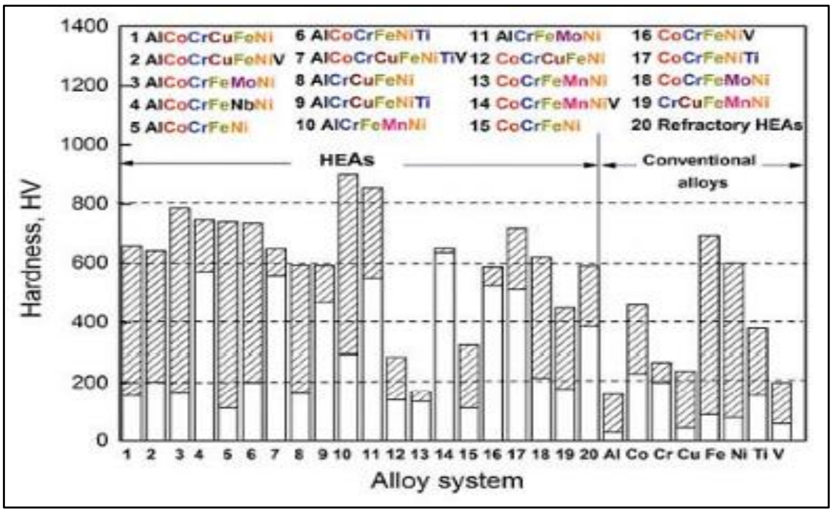

Figure 6. Hardness extremes and minimums of the most researched HEA systems [11]

3.4.2 Tensile properties

Tensile ductility typically increases when the temperature drops. The phrase "tensile ductility" can be used to characterize both the uniform plastic strain at the maximum load and the fracture-causing plastic strain, which also includes the uneven strain following necking.

3.4.3 Compressive properties

Since HEAs have exceptional mechanical properties, compressive characteristics are frequently researched at room and high temperatures. According to Yeh (2013) [23], HEA has variable behavior depending on temperature and strain rate. During compression tests, HEAs suggest the existence of several deformation processes [11].

3.4.4 Creep resistance

In high-temperature applications, creep is crucial because it behaves in line with the potential law when the temperature is high enough to allow dislocation movement but the viscous law when it is low enough to prohibit it. Often, HEAs show significant creep resistance [46].

3.4.5 Wear resistance

Wear is a significant issue since HEAs exhibit greater competitiveness and the ability to be used in tools, molds, and structural components.

Both sticky and abrasive environments have been examined to determine how HEAs wear [22]. The $Co_{1.5}CrFeNi_{1.5}Ti$ and $Al_{0.2}Co_{1.5}CrFeNi_{1.5}Ti$ alloys, according to Chuang et al. [48] exhibit more wear resistance than normal wear-resistant steels of the same hardness. These HEAs' extraordinary anti-oxidation and thermal softening resistance are thought to play a substantial role in their outstanding wear resistance. Alloying has the potential to affect the wear properties of HEAs [49].

3.4.6 Fatigue behavior

One of the most important variables that must be addressed and investigated in many prospective applications for HEAs is fatigue behavior and lifespan prediction, whether we are looking for use in the aerospace sector or other domains. In their investigation of the $Al_{0.5}CoCrCuFeNi$ HEA's fatigue behavior, Hemphill et al. [50] compared the results to those of other popular alloys, such as titanium alloys, advanced BMGs, and steels. Compared to steel, titanium, and nickel alloys, the bottom limit of the HEA fatigue ratios performs better than several Zr-based BMGs and zirconium alloys. Moreover, due to their brittle nature, some materials, such as wrought aluminum alloys and ultra-high-strength steels, have lower fatigue ratios despite having higher tensile strengths.

3.4.7 Corrosion resistance

According to Zhang et al. [22] and Heydari et al. [51], HEAs have excellent corrosion resistance. For starters, high entropy alloys have better corrosion resistance than several commonly used stainless steel types because their crystal structures tend to be simpler. Another factor is that many high entropy alloys have dendritic segregation structures, comprising a basic body structure and surface structure. Dendritic segregation structures also contain multiple disordered structures and nanoparticles. Introducing these structures has considerably increased the corrosion resistance of high entropy alloys. For instance, the considerably increased CoCrFeSi displayed improved corrosion resistance compared with stainless steel 304 in 1.0 mol/L NaCl and 0.5 mol/L H_2SO_4 solutions at ambient temperature [19].

3.4.8 Density

For many applications, alloy density is a crucial factor to consider. The densities of conventional alloys are frequently grouped according to the weights of the constituent elements: 2.7 g/cm^3 for aluminum alloys, 4.5 g/cm^3 for titanium alloys, 7.9 g/cm^3 for steels, and 8 to 9 g/cm^3 for superalloys based on nickel. Density is more equally distributed for CCAs. Light metal CCAs range in density from (2.67-5.21) g/cm^3, while refractory CCAs range from 5.59 to 13.75 g/cm^3. For MPEAs made of 3D transition metals, densities aren't typically measured. They normally range between 5.1 and 8.9 grams per cubic centimeter, under a weighted mixing rule. As a result, HEAs have favorable corrosion, electrochemical, wear-resistance, and oxidation behavior features [12, 52].

3.5 Functional properties

HEAs are recently created materials for which the study has only focused on the mechanical and microstructural aspects. On the functional qualities of the HEAs, some improvement is seen. These attributes include soft-magnetic properties, radiation resistance, catalytic properties, and thermoelectric qualities. These traits are influenced by their unique multi-principal element solid solution structure. The functional features are crucial for applications such as electromagnetic interference shielding, nuclear magnetic resonance, and solar plates. Examples of materials that help store hydrogen duels include CoFeMnTiVZr, TiZrNbMoV, HfNbTiVZr, and ZrTiVCrFeNi because they provide greater bulk density, increased safety, and reversibility in gas storage and sensing applications [14].

Soft magnetic materials [53-55] irradiation resistance materials [56-59], superconducting materials [60], photothermal conversion materials [61, 62], diffusion barrier films [63, 64] are only a few of the functional areas where HEAs have made significant strides.

4. OPERATING AT SEVERE WORKING EVENTS

In alloy engineering, the ideal alloy has a low density and high strength/ hardness [65]. In construction purposes like civil transportation and aeronautical engineering, lowering the weight of engineering elements is essential for reducing energy demand. Without HEAs, an aircraft corrodes, oxidizes, and cannot withstand extremely considerable temperatures [66]. Under typical operating conditions, power plants without HEAs as fuel cladding materials exhibit low thermal conductivity, a high thermal neutron absorption cross-section, and corrosion [67, 68].

An air foil bearing is an example of a part used at high temperatures but not requiring liquid lubrication. The system, which holds up the rotating shaft, comprises a top and a bump foil. The top foil and the journal, which are in touch with the shaft when it is stationary, are separated by a thin layer or gap when moving at higher speeds because of hydrodynamic pressure [69]. As a result, the bearing strikes the race at a slow rate during startup acceleration at standard temperature and shutdown deceleration at high temperature. These working circumstances are unpredictable. Thus, the materials must provide lubricity throughout a wide temperature range and long duration. A gas turbine engine's rolling element bearing and the bearing and piston of an automobile diesel engine all function at high temperatures similarly to air foil bearings [70]. Similar to gas turbine engines to work efficiently (requiring higher temperatures, faster speeds, and higher contact pressures), the design and operating circumstances of mechanical systems must be drastically revised [71-74].

5. APPLICATIONS OF HIGH ENTROPY ALLOYS

The unique properties of HEAs have sparked a lot of interest in mechanically and functionally orientated materials. A prospective future goal for HEAs is to design and build potential special applications to satisfy new requirements as opposed to merely replicating current performance [75]. Several HEA implementations are displayed in Table 1.

Table 1. Various HEA applications

HEA	Favorable Features	Ref.
Solar absorber coating	excellent absorption capacity, robust corrosion resistance, high-temperature mechanical properties, and outstanding strength and hardness	Yan & Zhang, (2020) [21] and Yin & Xu (2018) [19]
Diffusion barrier films	exceptional thermal stability and diffusion resistance	Yan & Zhang (2020) [21]
Aviation and turbine manufacturing (engine components, steam turbine blades, boiler pipes, heat exchanger tubes, aero engine components)	High efficiency, high solubility, hardness, great thermal stability, high-pressure, high-temperature materials, superconductivity and low density, outstanding cold formability and high strength-to-weight ratio	Abbaszadeh et al. (2020) [45] & Dada et al. (2021) [24]
Components of nuclear reactor	ion irradiation resistance, creep resistance, and less radioactive waste higher temperature strength	Dada et al., (2021) [24]
Marine ship vessels	Low specific energy requirements, improved workability, and the creation of HEAs with high melting points	Son et al. (2021) [76]
Coatings in the automobile sector	Higher bond strength, no phase shift, no aggregation, and a lower wear rate	Yin et al. (2019) [77] and Vladescu et al. (2016)
Tools and high-temperature applications	Larger ingots, higher purity, less energy use, and greater microstructural control	Mori et al. (2020) [78]
Coatings	high-temperature oxidation, hot corrosion resistance, thermal stability	Praveen & Kim (2017) [79]
The automotive and tiny electronics sector	Better surface finish, quick and effective	Gu et al. (2020) [80]
Welding	Better mechanical strength, low porosity	Rogal et al. (2017) [81]
Aerospace	high stress and high-temperature resistance	Zou et al. (2017) [82]
Biomedical materials (biological equipment, bio-ceramic materials)	excellent wear qualities, chemical stability, high hardness, strong biocompatibility, high stiffness	Ma, et al. (2020) [83]
Chemical plants	high-pressure, high-temperature materials, hardness, great thermal stability,	Ferrari & Körmann (2020) [84]
Structural applications (civilian infrastructure)	Low-temperature capabilities, improved permeability, and reasonable turnaround time	Rao et al. (2017) [85]
Austenitic Stainless steels (thermal protection sheets	Attractive and corrosion-resistant, it needs little maintenance and offers good strength, toughness, and fatigue properties	Miracle et al. (2014) [86] & Stiber et al. (2022) [87]
High loaded applications	fast heating, greater physical and mechanical performance, reduced energy use, and environmental friendliness	Guirong et al. (2021) [88]

A wide range of subjects pertaining to engineering, simulation, and materials science were covered. A unique vulnerability model for chemical production facilities was presented by [89], taking into account the synergistic impacts of overpressure and fire. Their paper highlighted the significance of comprehending and reducing hazards in chemical processing environments, and it was published in Reliability Engineering & System Safety. In their study [90], the authors provided crucial new information to the field of alloy development by examining the structure and hydrogen storage characteristics of a high-entropy alloy synthesized utilizing laser-engineered net shaping (LENS). Similar to this, [91] examined the mechanical and corrosion characteristics of a high-entropy AlCoCrFeNi alloy made by selective beam electron melting, offering crucial data for sophisticated manufacturing techniques.

Furthermore, research on the characteristics of different alloys and coatings was conducted by the studies [92-94], these studies looked at clamping fatigue, tribological performance, and microstructure modification. In addition, a thorough examination of materials and engineering aspects was demonstrated by the collection's works on finite element modelling [95-96], corrosion resistance of titanium alloys [97], creep damage models [98-100], and thermal barrier coatings [101]. The references also discussed the harmful effects of high-temperature protective coatings [102], jet engine pressure fluctuations, and aerospace engineering [103-106]. The understanding and development of materials and applications for engineering in diverse industries were aided by this array of studies.

6. CONCLUSION

HEAs proved their considerable effectiveness and remarkable efficiency and mechanical performance to be employed reliably and utilized under challenging working conditions. Nevertheless, the available global literature lacks rich knowledge respecting HEA characteristics, contributory properties, and substantial qualities. As a consequence, this work was performed to supply rich knowledge pertaining to HEAs, their evolution, core benefits, critical properties, and crucial applications. Because of their workability and serviceable qualities, HEAs have been utilized in the past, attracting more interest among the academic society. These valuable HEA characteristics are reflected in amended hardness, elevated strength, enhanced fatigue behavior, improved ductility, optimal molecular stability at escalated temperatures, and outstanding resistance to corrosion, wear, and oxidation. Hence, HEAs can be recognized as the material class with a considerable potential for reliable adoption and flexible application in various disciplines connected with aviation, maritime, and automotive industries.

Based on the outcomes attained from this scoping overview, it is recommended to carry out further research work and experimental explorations that can classify vital qualities and identify a variety of essential yields obtained from the engagement of those innovative materials into diversified engineering disciplines.

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