An Insight into High Entropy Alloys with a Focus on Friction Stir Processing

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Abstract. High entropy alloys (HEAs) have established an unprecedented stronghold in the domain of metallurgy in a relatively short span of time. The incoming era of engineering materials is expected to consist chiefly of these alloys, and therefore the research in this domain is ongoing extensively. Therefore, HEAs have been comprehensively discussed in the present work, covering from the fundamentals of entropy stabilization to the effect of micro-structural modification on specific properties such as wear, creep and fatigue strength. The evolution of HEAs has been elucidated, along with the applications, characterization techniques for their identification and scrutiny. The methods for fabrication of HEAs such as arc melting, magnetron sputtering, laser cladding etc. are included inclusively. Importantly, the role of friction stir processing (FSP) in the advancement of HEAs has been elaborated. FSP induces further heterogeneity in the HEAs, which help to overcome the strength-ductility trade-off. The intricate effect of FSP on micro-structural modification and the consequent effect on mechanical properties has been studied through the light of literature available on such investigations.

1. Introduction
The conventional strengthening mechanisms such as grain boundary, solid solution, heat treatment and cold work etc. induce a proportional sacrifice on ductility which is undesirable. Conventional metals and alloys bear an inverse relationship between the two important properties: Strength and ductility, consequently the strengthening is usually obtained at the cost of ductility and a strength-ductility trade-off is required for high strength at adequate ductility [1, 2]. Heterogeneity in the monolithic materials can accommodate contradicting properties. This has attracted a lot of researchers on designed multi-component and multiphase alloys [3], composites [4] and even bimodality to achieve high strength – ductility combination. The microstructural heterogeneity such as multimodality in grain size, morphology and/or chemical elements introduce heterogeneity. The introduction of particles of different materials into a substrate via solid state processing by Friction Stir Processing (FSP) is a common route which can introduce some kind of heterogeneities [5-7].
High entropy alloys (HEAs) design-based materials which possess multiple-element as nearly equiatomic concentration in single phase solid solution systems with heterogeneity of atomic distribution [8, 9]. The constituent elements may be present in single parent lattices face-centered cubic (FCC) (in FCC HEAs), body-centered cubic (in BCC HEAs) or hexagonal close packed (in HCP HEAs) structures. The HEAs inherit major property associated with the parent lattice. Multi-element systems usually possess brittle intermetallic phases which are detrimental, whereas the solid solution tendency in HEAs retards the formation detrimental IMCs. The exceptional properties possessed by HEAs such as hot strength [10, 11], combination of high strength and ductility in cryogenic conditions [12], excellent fatigue resistance [13], and corrosion resistance [14, 15], through multi-phase or eutectic-structure design. The original HEAs are recent design-based materials about one-an-half decade old [8, 16]. They are designed on the principles that single-phase solid solution of multiple principal elements maximized configurational entropy and result in a massive single solid solution phase [17]. The condition of equi-atomic concentration of principal elements in a single phase has put a very strict restriction on the production of HEAs and it has also limited a vast space which may provide favorable properties in the condition of equi-atomic concentration condition are removed. Generally, the HEAs are produced via initial liquid phase such as by casting, plasma arc melting and additive manufacturing etc. Of late alloying via solid state routes such as powder metallurgy, milling and have also attracted the attention. The friction-stir processing (FSP) route has attracted a lot of attraction in the homogenization of the cast structure of HEAs. Other severe plastic deformation (SPD) processes such as equal channel angular pressing (ECAP) [18] and high-pressure torsion (HPT) [19] are reported to refine the structure of HEAs which result in significant improvement in mechanical properties and mainly strength. The variation in strain at different radial distances from the tool center [20] coupled with intense stirring during FSP produces alloying effect with extensive heterogeneity in elemental concentration and grain size [21]. The effect of homogeneous solid solution in varying elemental concentration and bimodality distribution has been demonstrated in case of CuNiMgZn based systems. The solid-state routes rely non-equilibrium diffusion under conditions of pressure, temperature and plastic deformation and are generally referred to as mechanical alloying (MA). Unlike regular alloys, the HEAs with heterogeneity show excellent tunability to deformation by adjusting it in the phase variation caused by: chemical concentration, transformation induced plasticity (TRIP) and grain boundary area variations etc. The change in mechanical properties vary due to heterogeneity assisted tunability which is substantially different for BCC [22, 23]/FCC [24] and HCP HEAs [25]. The HEAs are generally produced by melting in vacuum furnace by using pure metals with a nominal composition at% concentrations followed by casting. The cast ingot may be subsequently treated to produce the HEAs in desired TRIP state. A typical treatment may comprise of: (i) hot-rolling (at 900 °C) to 50% thickness of 50%, (ii) homogenization at 1200 C for 5 h in Ar atmosphere followed by (iii) quenching in ice water (Figure 1).
Originally the HEAs are defined as equiatomic alloys with high configurational entropy of mixing (ΔS_{mix} > 1.5R (R=8.31 J K^{-1} mol^{-1}, the gas constant)) to overcome the effect of enthalpy [26]. There are common alloys with non-equiatomic high concentration MEAs. Some conventional alloys containing high concentrations of alloying elements such as 316 steel (1.15 R), Inconel 718 superalloy (1.31 R), Stellite 6 superalloy (1.13 R). These alloys possess values of (ΔS_{mix}) between R and 1.5R and are known as medium entropy alloys MEAs [27]. The low entropy alloys have the value of (ΔS_{mix}) < R. Unlike solid solution and phase rules for conventional solid solution systems, the phase formation in HEAs are governed not only by configurational entropy of mixing, but also by mismatch entropy, mixing enthalpy, atomic size difference, valency and electronegativity [12, 28]. The solid solution is stable when the difference in atomic size is small and mixing enthalpy is negligible.

Configurational entropy of mixing for a material refers to the distinguishable ways in which the atoms can be arranged in a lattice. The large value of ΔS_{mix} decreases the free energy substantially and stabilizes solid solution phases. Mixing of two different elements placed in physical contact leads to the increase of entropy and which can be ascertained by Boltzmann’s hypothesis [29] as per Eqn-(1).

\[ \Delta S_{mix} = -R \sum_{i=1}^{n} x_i \log x_i \] (1)

where R is the gas constant, n is the number of total elements, \( x_i \) is the concentration of element i.

Manufacturing of HEAs by MA has been demonstrated as early as in 2008 [30]. The MA is normally utilized to produce the HEA nanoparticles which are wear resistant and useful in bearing applications. The soft-phase (e.g. Bi) and solid lubricant phase (e.g. MoS_2 etc.) dispersion in HEA matrix such as HEA-Pb, and HEA-Bi system are known to be effective in enhancing wear resistance [31]. The MA is mainly used to synthesize nano-structured HEA in nano-powder form. The HEA nano-powder is subsequently consolidated into bulk HEAs by various techniques but generally spark plasma sintering (SPS). The HEAs are known for slower diffusion but are metastable in nature due to which if SPS not performed under desirable conditions of pressure, heating rate, sintering temperature and cooling rate it will risk phase transformation and the property gain may be lost. A sintering temperature with lower heating rate is advantageous for optimum density and homogenous nanocrystalline microstructure. The sintering pressure of the order of 30-50 MPa is found to provide adequate densification. If the heating temperature and heating rate is not appropriate, a phase transformation during subsequent cooling may be disastrous to the HEA effect.

2. HEAs Evolution and Categories

As shown in Figure 2, one predominant element was combined with other elements in small amounts in the initial stages of alloying to enhance unique properties. Iron (Fe) alloys, copper (Cu) alloys, aluminum (Al) alloys, magnesium (Mg) alloys, titanium (Ti) alloys, and nickel (Ni) alloys are few of the common or essential alloys. Human discovery of metallic materials began with pure metals (e.g., Cu), then progressed to binary (e.g., Fe-Cu, Cu-Ni, etc.), ternary (e.g., Ni-chromium (Cr)-Al), quaternary (e.g., Ni-cobalt (Co)-Al-Cr, Cr-Fe-Co-Ni, Al-Cr-Co-Ni, Al-Fe-Co-Ni, Al-Cr-Fe-Co, etc.), quinary (e.g., Ni-Fe-Cr-Ti-Al, Al-Cr-Fe-Co-Ni, Cr- Manganese (Mn)-Fe-Co-Ni, etc.), and higher-order alloys to achieve favorable properties in order to meet ever-increasing demands [32, 33]. Binary and ternary alloys are the most common types of conventional alloys. A binary alloy is described as a blend of only two types of constituents, while a ternary alloy is made up of three different kinds of elements such as Fe, Ni, and Cr. Ternary alloys of Fe and Ni with Cr and Al are the most important materials for many high temperature applications, especially for gas turbines [34]. Likewise, a quaternary alloy is made up of four constituents, whereas a quinary alloy is made up of five. The complexity of the elemental composition in alloys has been gradually increasing over time as shown in Figure 2 [35, 36].
HEAs are the latest trend, and they are characterized as materials with complex multi-element compositions. In comparison to traditional alloys, they have a striking functionality and their high structure entropy mixing is more stable at high temperatures. Figure 3 shows the X-ray Powder Diffraction (XRD) trends of a range of binary to septenary alloys, demonstrating the high-entropy effect [37]. In quinary, senary (six constituents), and septenary (seven elements) alloys, the phases are relatively simple: there are only two major phases, both of which have simple structures such as body-centered cubic (BCC) and Face Centered Cubic Structure (FCC). The presence of such basic structures defies perceptions that there might be a development of a number of binary and ternary compounds in HEAs. Generally, FCC-type HEAs are soft and malleable and the BCC-type HEAs have high strength but are usually brittle [37]. Aside from the high entropy effect, another important characteristic for HEAs is their significant lattice distortion, which is caused by a large atomic size discrepancy between the constituent alloying elements.

As an example, all the possible quaternary, ternary, binary, and pure metal subsets of the quinary high-entropy alloy Fe-Ni-Co-Cr-Mn (also known as Cantor alloy) is shown in Figure 4 [39]. Equi-atomic Fe-Ni-Co-Cr-Mn alloy has been reported to display promising strength and ductility at cryogenic temperature as well as it exhibits single-phase with a FCC crystal structure [40].
3. Properties and applications
HEAs exhibit excellent combinations of strength, ductility, oxidation resistance, and thermal Stability. They have the potential as functional and structural materials for wide range of applications. In conventional alloys the dominant material defines the material properties and other minor alloying elements enhance some of the properties. Whereas in case of HEAs it is the structure type that define and control the material properties. Small alloying elements can also be added to HEAs to increase or decrease a particular property, but it may result in unwanted effects on the other properties [41]. In general BCC-structured HEAs have very high yield strengths and limited plasticity, whereas the FCC structured HEAs have low yield strength and high plasticity. The mixture of both BCC and FCC have shown high yield strength and good ductility. HEAs are mostly more prone to phase transformation under applied temperature or stress, which could be used to trigger interesting plasticity mechanisms as well as to accommodate larger strains. HEAs exhibit high melting points, and sustain high yield strengths even at high temperatures. Senkov et al. [42] produced BCC based Nb_{25}Mo_{25}Ta_{25}W_{25} and V_{20}Nb_{20}Mo_{20}Ta_{20}W_{20}, refractory HEAs through vacuum arc-melting. The yield strength of fabricated HEAs were found to much higher as compared to the super alloys especially at higher temperatures as shown in Figure 5 [42]. Refractory metal HEAs find applications in thermal barrier coatings.

The mechanical properties of HEAs are well within those observed in martensitic steels, advanced high strength steels, nickel-based alloys, etc. However, HEAs with superior properties can be obtained with further optimizations. Several studies have reported HEAs with high hardness and high compressive strength both at room temperature and elevated temperatures [10, 43]. Senkov et al. [43] produced a refractory alloy, Ta_{20}Nb_{20}Hf_{20}Zr_{20}Ti_{20} with predominantly a BCC structure by vacuum arc-melting followed by hot isostatic. The alloy was found to have high compression yield strength and ductility. In addition to the structure types, alloying effect and cooling temperature also effect the
mechanical behavior of the HEAs at room temperature. Ma and Zhang [41] studied the effect of Nb addition on the microstructure and properties of AlCoCrFeNi HEAs. The results showed formation of two phases; one BCC solid solution phase and other the Laves phase of (CoCr)Nb type. The compressive yield strength and Vickers hardness were found to increase almost linearly with increasing Nb content. Wang et al. [44] studied the cooling rate and size effect on the microstructure and properties of the AlCoCrFeNi HEAs. Higher cooling rates were linked to uniform microstructures and slight increase in both the strength and the plasticity. Whereas heat treatment induces the grain refinements in the microstructure and influence the mechanical behavior at elevated temperatures. The heat treated HEAs have fine granular structure. They demonstrate homogeneous flow, great resistance to necking and exceptional elongations [45].

Fatigue behavior of the HEAs is comparable with that of conventional alloys and bulk metallic glasses. Some HEAs exhibit fatigue resistance favorable to that of austenitic stainless steels and TWIP steels [46]. Due to the high fatigue resistance they have potential applications in aerospace and automobile industries. In general, HEAs have a fatigue endurance limit of between 540 and 945 MPa and the ratio of fatigue endurance limit to ultimate tensile strength between 0.402 and 0.703. The lower bound of the fatigue ratios are comparable to steel, titanium and nickel alloys and outperforms zirconium alloys. Higher fatigue strength of HEAs is attributed to their higher tensile strength [47]. HEAs have excellent wear resistance properties with potential applications in tools, molds and structural components. Chuang et al. [15] reported the wear resistance of the Co1.5CrFeNi1.5Ti and Al0.2Co1.5CrFeNi1.5Ti alloys to be around two times better than that of conventional wear-resistant steels such as SUJ2 and SKH51. The excellent anti-oxidation property and resistance to thermal softening in these high-entropy alloys were considered to be the main reasons for the outstanding wear resistance. Furthermore, alloying also affects the wear behavior. Wu et al. [48] investigated the wear behavior of AlxCoCrCuFeNi with varying Al content. Higher Al content was found to increase the volume fraction of BCC phase, hardness, and thus the wear resistance. Some HEAs can exhibit ferromagnetic properties [41], and super-paramagnetic properties [49] and hence have potential for electronic applications.

| HEA under consideration | Author | Investigated properties |
|-------------------------|--------|------------------------|
| Nb25Mo25Ta25W25 and V20NbMo20Ta20W20 | Senkov et al. [42] | Mechanical properties of refractory HEAs |
| TaNbHfZrTi | Senkov et al. [43] | Microstructure and room temperature properties |
| TaNbHfZrTi | Senkov et al. [10] | Microstructure and elevated temperature properties |
| AlCoCrFeNi | Wang et al. [44] | Cooling rate and size effect on microstructure and properties |
| AlCoCrFeNi | Ma and Zhang [41] | Ferromagnetic properties |
| AlCrCuNiFeCo | Kuznetsov [45] | Tensile properties |
| CrMnFeCoNi | Thurston [46] | Fatigue resistance |
| Al0.5CoCrCuFeNi | Hemphill et al. [47] | Fatigue behavior |
| Co1.5CrFeNi1.5Ti and Al0.2Co1.5CrFeNi1.5Ti | Chuang et al. [15] | Wear behavior |
| AlxCoCrCuFeNi | Wu et al. [48] | Wear behavior as a function of aluminum content |
| CoCrCuFeNiTiX | Wang et al. [49] | Super-paramagnetic properties |
4. Major characterization techniques employed to identify HEAs, inter-metallic compounds

Microstructure of HEAs vary based on the fabrication technique, heat treatment, and other operations such as rolling or forging. Since microstructure is the key factor which governs the material properties, a detailed characterization of the microstructure is essential in order to interpret the material properties. Moreover, since the phase structure of HEAs strongly influence the performance and applications it is imperative to understand phase structures in order to design HEAs with specific properties. Phases in HEAs are usually solid solution, intermetallic compounds, amorphous alloy or a combination of them. BCC, FCC and sometimes HCP constitute the solid phases. Whereas in case of intermetallic there are various m, c and laves phase. The SEM analysis is generally carried out for the microstructural studies, chemical composition is characterized by the EDS. The phases and their constituents are characterized by XRD and TEM studies. The grain morphology and surface integrity of HEAs are generally characterized using AFM analysis.

Ye et al. [50] produced Al$_x$FeCoNiCuCr HEA using laser cladding with varying Al content. Microstructural and compositional analysis was performed using SEM. The SEM analysis revealed the presence of both dendritic (DR) and interdendritic (ID) areas as shown in Figure 6. The interdendritic segregation in the HEA produced by laser cladding were found to be smaller than that of casting route. Since the interdendritic segregation causes adverse impacts on the performance of the alloy, HEAs fabricated by laser cladding were proposed to have better performance than the casting ones. XRD and TEM analysis revealed the influence of Al content on the phase composition. Figure 7 shows the XRD peaks with phase compositions for varying Al content in Al$_x$FeCoNiCuCr HEA [12]. In case of HEAs for high temperature applications it is required to study the time-dependent plastic deformation of materials. Creep test using nanoindentation equipment with a spherical tip is generally incorporated for the characterization. Ma et al. [51], studied the creep behavior of CoCrFeCuNi HEA in as-deposited and 800 K annealed state using nano-indentation. It was found that both the internal structure and external loading sequence strongly affect the creep behavior.

![Image](image_url)

**Figure 6.** Microstructure of Al$_x$FeCoNiCuCr HEA with (a) Al 1.0 (b) Al 1.3 [12].

![Image](image_url)

**Figure 7.** XRD peaks showing the effect of Al content on the phase composition [12].
5. Major routes/methods of manufacturing HEAs

The techniques to produce bulk HEAs from the liquid state involve melting and solidification processes [52]. The solid pure metals are transformed into a liquid state and uniformly blended during the melting process. The liquid mixture is then solidified to develop bulk alloys under various cooling conditions. Another method is to make bulk HEAs from a solid-state, which can be done through powder metallurgy. Furthermore, arc-melting, which has over two hundred documented studies, is the most popular synthesis routes for forming bulk HEAs [53]. HEA coatings can also be manufactured using magnetron sputtering and laser cladding, while small-scale bulk HEAs are produced using splat quenching, laser cladding, and powder metallurgy. The sections that follow outline several of the approaches used in the fabrication or processing of HEAs.

5.1. Arc melting

Vacuum arc melting is widely used to produce alloys with lower melting temperatures. The first and the key method for preparing HEAs is vacuum arc furnace smelting and copper mold casting [54]. The HEAs produced by vacuum arc melting had a clear crystal structure with exceptional properties in terms of microstructure, mechanical properties, and corrosion resistance [55]. Ma et al. [56] used arc melting to make Al0.5CrCuFeNi2 HEAs. Clear FCC solid solution with a dendrite microstructure was observed in the as-cast sample. Senkov et al. [42] developed the refractory NbCrMo0.5Ta0.5TiZr, Nb25Mo25Ta25W25, and V20Nb20Mo20Ta20W20 alloys [57, 58]. The single-phase BCC structure was present in both Nb25Mo25Ta25W25 and V20Nb20Mo20Ta20W20 alloys. Zhang et al. [59] also used an arc melting process to form CrFeVTa0.2W0.2 and CrFeVTa0.1W0.1 alloy, which had superior heat-softening tolerance.

5.2. Bridgman solidification

The Bridgman method is also used to make single-crystal ingots or boules. The method entails heating a material well above the melting point in a container and then cooling it gradually from one side, where a seed crystal is positioned. All along the length of the container, single-crystal material is gradually shaped. The procedure may be performed in either a horizontal or vertical configuration. In a high-pressure furnace, the Bridgman process melts the alloy to the desired composition. There are three temperature zones in the Bridgman furnace. Temperatures above the melting point define the upper region, while the lower zone is cooler than the melting point. As a buffer between the two, an adiabatic zone is used.

Bridgman solidification technology can monitor the growth direction and rate of alloy crystal during the solidification by changing the heat flow direction, temperature gradient, and pulling speed of the solid-liquid interface, resulting in improved alloy structure and properties. Ma et al. [60] effectively prepared single-crystal CoCrFeNiAl0.3 and CoCrFeNiAl HEAs using the Bridgman solidification method. By using the same technique, Zuo et al. [61] also generated FeCoNiAlSi HEAs. As compared to samples produced by arc melting, the alloy's soft magnetic properties were enhanced in the Bridgman solidification approach.

5.3. High gravity combustion synthesis

Li et al. [62] proposed another technique for preparing HEAs using combustion synthesis in a high-gravity setting. The crucible was placed on a Ni-based superalloy rotor with two internal cavities: one for carrying the sample and the other for balancing the opposite sample in this process. The void between the graphite crucible and the cavity wall inside the rotor disk was filled with heat-insulating materials. Once the centrifuge had given a centrifugal force in the combustion chambers greater than 1500g, the chamber device was discharged to a vacuum of about 100 Pa and then ignited with the W wire. The reactive mixtures melted due to the reaction heat and high gravity, and the metal melts were segregated due to the density differential. Eventually, glass ceramics and bulk metal ingots were collected. After that, the metals were machined and polished in preparation for future experiments. CoCrFeNi and AlCoCrFeNi HEAs was produced by high-gravity combustion synthesis.
5.4. Magnetron sputtering
Magnetron sputtering involves bombarding a material's surface with a high-energy particle [55]. Argon can ionize argon-ion and electrons when exposed to a strong electric field. Then, in an electric field, ions are propelled toward the cathode, bombarding the target surface with high energy, causing sputtering. When placed in a magnetic field and an electric field with orthogonal distribution, the target material releases secondary electrons. As a result, the target material ionizes more ions, allowing the bombardment to intensify.

5.5. Laser cladding
Zhang et al. [63] documented a low-cost HEA coating made by laser cladding with a nominal composition of 6FeNiCoCrAlTiSi. An energy source is used to melt the feedstock until it is added to a substrate [64]. The heat source is a directed laser beam, which melts the substrate upon which the feedstock is applied. This technique usually produces a metallurgical bond with higher bond strength. The result is a thick coating with no gaps or porosity. One of the benefits of the laser cladding process is that the laser beam can be directed and localized to a very small region, resulting in a minimal heat-affected zone on the substrate. Furthermore, the lower overall heat decreases the dilution of the coating with substrate materials. The laser-cladding produced coating has a simple BCC solid solution with high micro-hardness, higher softening resistance, and elevated electrical resistivity [65].

5.6. Additive Manufacturing
In addition to the intensive processing requirements of the aforementioned methods, it could be argued that these techniques restrict the shape and size of HEA components. The new development is an additive manufacturing (AM), which can manufacture complex near-net shape components. Kunce et al. developed bulk TiZrNbMoV [66] and ZrTiVCrFeNi [67] alloys through AM. Direct laser manufacturing (DLF) was used by Joseph et al. [53] to manufacture bulk AlxCoCrFeNi HEAs. The feedstock or the raw material in AM is usually pre-alloyed HEA wires or HEA powders. High-energy sources, such as lasers or electron beams, fuse the feedstock. These power sources can reach high temperatures to melt refractory elements quickly and help reduce the evaporation of the elements with lower melting points. AM technologies such as laser metal deposition (LMD), selective laser melting (SLM), and electron beam melting (EBM) are widely used to fabricate HEAs. LMD was used by Xiang et al. [68] to prepare CrMnFeCoNi HEA and Zhu et al. [69] prepared the same alloy using SLM and discovered that the mechanical properties of the HEA were improved. The additively produced HEA exhibits a remarkable combination of high strength and excellent ductility.

5.7. Friction Stir Processing
Friction stir processing (FSP) is perhaps the most commercially viable thermo-mechanical processing technique for bulk materials, and it can be used for solid-state joining. FSP is a simple, clean, and eco-friendly solid-state processing technique [70]. Figure 8 depicts a diagram of the FSP operation. FSP is a solid-state process in which a specially built rotating cylindrical tool composed of a shoulder with an attached pin is plunged into the processed plate. Friction produces heat at the interface between the shoulder and the processed workpiece, softening the material. The material is stirred by the spinning pin, and the process is completed by the tool moving over the sample. At a high temperature, the material undergoes extreme plastic deformation during the process.
FSP can be used to improve HEA's mechanical and microstructural properties even further. For example, Li et al. [70] made a novel Al matrix composite reinforced with Al0.8CoCrFeNi HEA particles, and Gao et al. [72] used a multi-pass FSP to fabricate Fe-Co-Ni-Cr-Al HEA reinforced Al5083 composites. The XRD outcomes revealed that FSP technology can be used to make HEA reinforced Al matrix composites that are free of intermetallics. The composites manufactured from FSP had greater microhardness, yield strength, ultimate tensile strength, and wear resistance than the base alloy and FSPed samples without the HEA particles, according to the findings. Besides, Kumar et al. [20] used FSP to manipulate the microstructure of a HEA. This study aimed to see how microstructural refinement using FSP affected the plastic deformation behavior of a HEA. The HEA displayed an excellent combination of strength and ductility in the FSP condition, as well as high values of friction stress and Hall–Petch coefficient, suggesting that grain refinement can be a very powerful HEA strengthening mechanism. The FSP-engineered microstructure of the transformation-induced plasticity (TRIP) assisted HEA with composition Fe_{50}Mn_{30}Co_{10}Cr_{10} (at. %) had a significantly smaller grain size, and optimized fractions of FCC and hexagonal close-packed (hcp) phases [25].

The effect of friction stir welding (FSW) parameters on the structure and properties of Fe_{50}Mn_{30}Cr_{10}Co_{10}C_{1} HEA welds was investigated by Shaysultanov et al. [73]. FSW of the alloy resulted in recrystallization of the stir zone and a reduction in the fraction of the carbides to 1–2%; however, the percentage of the hcp phase remained virtually unchanged from the initial state. Yang et al. [74] used cooling-assisted FSP to manufacture HEA-reinforced aluminum alloy surface composites. The impact of HEA particle volume fraction on microstructure, microhardness, and tribological properties was investigated. Hardness and wear resistance strengthened as the volume fraction of HEA particles improved. Nair et al. [75] conducted the FSP of an Al0.1CoCrFeNi HEA under monitored cooling conditions. Because of the substantial grain refinement, the hardness of processed HEA was significantly higher than that of as-cast HEA. The processed HEA’s improved erosion resistance is linked to their increased hardness, plasticity resistance, and yield strength than the as-cast HEA. The prospect of utilizing FSW as a welding technique to achieve strong joints in HEAs was explored by Zhu et al. [76, 77]. Using this method, the authors were able to weld Co16Cr28Fe28Ni28 and CoCrFeNiAl0.3 HEAs. Finally, grain refinement, progressive recrystallization, hardness improvement, ductility reduction, and material strengthening are some of the advantages that can be associated with the FSP of HEAs [78].

6. Conclusions
The literature encompassing friction stir processing of HEAs has been expounded in the present work, along with a rudimentary perspective of these modern-day engineering materials. Various techniques of manufacturing the HEAs are discussed with their methodology and principles of fabrication. The review suggests that more innovative technologies are likely to evolve for their production, wherein avoiding the formation of detrimental intermetallic compounds is among the primary concerns.
Friction stir processing tremendously enhances the micro-structural and mechanical aspects of these alloys. HEAs have the potential to replace superalloys in the aerospace sectors, and are also excellent refractory materials. Modern characterization techniques such as atomic force microscopy and nano-indentation are vital to the research and development of these alloys.

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