A critical review on mechanically alloyed high entropy alloys: processing challenges and properties

Akshay Kumar, Alok Singh and Amit Suhane

Abstract

High entropy alloys are an innovative class of materials for a wide range of industrial applications due to their competitive properties such as improved mechanical properties, superior wear resistance characteristics, and excellent corrosion behavior, which are widely desired for a variety of applications considering several attributes such as economical, eco-friendly and safety. Thus, the quest for high-performance materials with exceptional properties is an unfading research topic for researchers, academia, and metallurgical scientists. HEA presents a novel alloy design idea focused on multi principal elements, a huge compositional space, and more opportunities to develop diverse alloys with exceptional properties. As universally acknowledged, the immense potential in compositions, microstructures, and properties has sparked a great interest in this field. Researchers primarily focused on equimolar HEAs, but the precedent eventually shifted to non-equimolar alloys. As the investigation over HEAs progressed, four core effects were identified as the most important aspects in enabling the distinct characteristics. Mechanical alloying (MA), followed by the sintering approach, has piqued the interest of all researchers focusing on HEA development. As a result, the main intent of this study is to examine mechanically alloyed HEAs critically for mechanical properties, tribological behavior, corrosion behavior, and functional properties. Furthermore, the predominant challenges and their conceivable prospects are also deliberated that offer novelty to this review article.

1. Introduction

Materials have played a vital role in nearly every aspect of human life throughout history. High-strength materials have been extensively sought after for structural components to enhance load-bearing capabilities while minimizing weight. Aside from strength, the material should have high ductility and hardness for shaping into diverse forms and preventing the catastrophic breakdown of components in service. For instance, one of the major objectives of the automobile sector is to enhance fuel efficiency and minimize ecologically damaging emissions by lowering the weight of components without compromising safety concerns [1]. Figure 1 represents the current scenario in the field of materials with time.

Material science and engineering have alloyed pure metals with two or three elements for decades [2, 3] one of which is the major element in greater concentration and the other is the secondary element in a lower concentration. Several irons, copper, Nickel, titanium, magnesium, and aluminium alloys have been synthesized and examined for strength, thermal stability, and wear behavior, according to several research publications [4–8]. HEAs have piqued the interest of academia and scientists because of their remarkable properties over conventional alloys [9, 10]. These characteristics are not limited to improved hardness [11], but also include substantially enhanced strength, higher fatigue [12], plasticity [13], stability at high temperatures, excellent resistance to corrosion [14], wear, and oxidation [15]. As a result, HEAs are widely recognized as the most innovative material family, with a broad array of applications spanning from automobile to maritime [16, 17].
HEAs can be synthesized through liquid state processing, thin-film deposition techniques, additive manufacturing, and solid-state processing techniques. In liquid state processing techniques vacuum arc melting and induction melting are mainly reported. In liquid state processing, metallic alloy ingots or powder elements are heated in an electric furnace or by tungsten electric arc under an argon atmosphere to avoid oxidation [19]. However, there are certain limitations with liquid state processing are reported a) evaporation of low melting point b) due to low solidification rate formation of heterogenous compounds. Whereas thin film deposition technique is used to fabricate coatings of refractory elements over the substrate to enhance the properties [20]. Pulse laser deposition (PLD) [21], magnetron sputtering deposition (MSD) [20], and plasma spraying deposition [22] are some thin film deposition techniques. In additive manufacturing techniques, the development of intricate shape components takes place through the layer-by-layer deposition of molten metal [23]. This technique is adopted to develop internal cavity parts, complex geometrical shapes while maintaining a high level of accuracy. Different techniques of additive manufacturing explicitly reported are 3D plotting, selective laser
Table 1. Discussion of salient features of HEAs processed through different synthesis techniques.

| S. No. | HEA | Synthesis technique | Favorable | Adverse | Key outcomes | Applications | References |
|--------|-----|---------------------|-----------|---------|--------------|--------------|------------|
| 1.     | CoFeNiCrMn, AlCoCrFeNi | Cold spraying | No aggregation, no phase transition, stronger bond strength, and rate of wear is lesser | Porosity, minimal plasticity, high machinery cost | Lower wear rate, operability at elevated temperature | Coatings on tools | [30, 31] |
| 2.     | AlCoCrFeNi, Al0.5CrMoNbTa0.5 | Electron Beam Melting | Remarkable microstructural stability, higher purity, larger ingots, reduced energy usage | Material wastage, brittle product, restricted alloying | Tensile strength 197 MPa, homogenized structure with minimal porosity | Gears, and tools | [25, 32] |
| 3.     | Al0.5CoCrFeNi, Al1.3CoCuFeNi2, Al0.5Cr0.9FeNi2.5V0.2, AlCoCrFeNi | Arc melting | Highly effective, with a higher solubility level | Producing a complicated composition is complex | lower diffusion rate | Aerospace and turbine development | [11, 15, 33, 34] |
| 4.     | CrMnCoFeNi-WC, AlCoCrFeNi | Laser melting deposition | Grain refinement, intricate geometries, equiaxed grains, uniform composition, | Toxic in nature | Tensile strength 0.8 GPa | Coatings | [13, 35] |
| 5.     | AlCrCoFeNi, Al0.5CoCrFeNiCo, CrMnFeCoNi, MgMnAlZnCu | Induction melting | The higher recovery rate of elements, removal of non-metallic inclusions and gases | Scouring & erosion of the slag, short span life of the crucible | Microhardness & specific wears were 10.78 GPa and 9.6 × 10^-5 mm³ N^-1 m^-1 | Structural applications at the cryogenic condition | [36–39] |
| 6.     | CoCrFeMnNi, WC-(Al)CoCrCuFeNi, (AlCoCrFeNi)100-xCo_x (FeCoNiCrMn)100-xAl_x | Vacuum arc melting | Minimal relative power utilization, improved workability, and the production of HEAs having high melting points | Grain refinement was restricted, melting was problematic, and electrode production costs were significant | Anti-fouling capabilities, fracture strain improved | Marine, ship vessels | [40–43] |
| 7.     | MgMoNbFeTi1.5Y1.5, CoCrCu1.5FeNi5 | Laser Cladding | High strength, durability, & reliability | Under performance | High Hardness | Automobile Frames, light weight application | [44, 45] |
| S. No. | HEA                        | Synthesis technique                              | Favorable                                                                                         | Adverse                                                                                         | Key outcomes                    | Applications                  | References |
|-------|----------------------------|--------------------------------------------------|---------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|---------------------------------|--------------------------------|------------|
| 8.    | CoCrFeNi, AlCoCrCuFeNiSi  | Gas atomization tailed spark plasma sintering    | Increased thermal conductivity, uniform particle dispersion, improved wear resistance           | Confined for smaller products, symmetrical and simple geometries.                               | Compressive strength 921 MPa, Hardness 271 HV | Nuclear power plant equipments | [46, 47]  |
| 9.    | AlCoCrFeNi, CoCrFeNi, AlCoCrCuFeNiSi₆ | Mechanical alloyed followed Spark plasma sintering | Compaction and sintering were completed in a single process, resulting in uniform particle dispersion | Suitable for symmetric geometries                                                               | self-lubricating property, Compressive strength 1.537 GPa,                                      | Alloy wheels, pulleys                  | [46, 48, 49] |
| 10.   | AlₓCoCrFeNi               | Friction stir processing                          | Performed below melting point temperature, eco-friendly and highly energy efficient              | Less flexible, complicated fixture arrangement                                              | Yield strength 525 ± 31, ultimate tensile stress 784 ± 28 MPa, total elongation 37 ± 8         | Heavy-duty vehicles, tools                  | [50]       |
| 11.   | CoCrFeMnNi, FeCoCrNiMn    | MA followed by hot isostatic sintering            | Lower porosity, higher mechanical strength                                                     | greater power consumption, and Time-consuming                                                   | Higher Compressive strength     | Weldings                                  | [51, 52]  |
| 12.   | AlₓCrₓ₄CuFe₀.₄Mnₓ, FeCoNiSi₆ | Copper mold casting                             | Low-temperature capabilities, increased permeability, and reasonable turn-around time           | Product geometry flexibility is limited, and production costs are expensive                      | High Yield ultimate tensile strength                                                        | Structural applications                      | [53, 54]  |
| 13.   | FeCoNi₁₃Cu₁₂₃Bₓ, AlCoCrFeNi | Cold isostatic pressure followed microwave sintering | improved diffusion mechanisms, enhanced mechanical properties, decreased power usage, and eco-friendly | problematic for ceramics elements, Costly equipment                                             | Compression strength 1.546 GPa, hardness 367.1 HV                                           | High load applications                           | [55, 56]  |
| 14.   | AlₓCoCrFeNi, AlCrCuNiFeCo | Casting route                                     | Any shape produces, the cheaper initial cost                                                   | Only viable for large scale production, casting defects, deformities, and insufficiencies      | Yield stress and ultimate tensile strength 1040 MPa, 1170 MPa respectively                   | Manufacturing equipment, ship buildings           | [57, 58]  |
melting (SLM) [24], electron beam melting [25], direct energy deposition (DED) [26]. Whereas the development
of HEAs solid-state processing technique is widely adopted and explicitly reported. Figure 2 depicts the layout
for the development of HEAs through different processing routes. In the processing of HEAs, through the SPS
technique, the fine metallic powder is mixed at room temperature followed by consolidation at high
temperature. The SSP technique includes powder development (atomization and mechanical alloying), followed
by compaction (consolidation of fine HEA metallic powder) via different processes such as hot pressing [27],
cold isostatic [28], and uniaxial pressing [29]. However, in the last decade, an exponential rise in research articles
over mechanical alloyed high entropy alloys are reported. Table 1 also discusses the different HEAs synthesized
using distinct methods, as well as their important properties and relevance.

The present state of published scientific literature on MA synthesis of different HEAs is shown in figure 3.
The impact of MA and its variables on HEA performance has gotten very little research. As a result, a thorough
analysis of MA’s significance in the development of HEAs, as well as their properties, has been made. This
article’s summary may be stated as follows: it began with a quick introduction to the various processing pathways
used for HEAs, as well as fundamental definitions of HEAs. In brief, discussed mechanical alloying and phase

| S.No. | Aspects                | HEAs                      | Conventional dilute alloys |
|-------|------------------------|---------------------------|----------------------------|
| 1.    | Compositional space    | High- and hyper-dimensional | Low-dimensional           |
| 2.    | Alloy design strategy  | Based on multi principal elements | Based on one or two principal elements |
| 3.    | Solid solution         | Undistinguishable solvent and solute atoms | Distinguishable solvent and solute atoms |
| 4.    | Composition            | Limitless                 | Restricted                 |
| 5.    | Concentration of secondary elements | Concentrated         | Dilute                     |
| 6.    | Phase diagram          | Central region            | Edges & corner             |
| 7.    | Modulus mismatch       | Severe                    | Average                    |
| 8.    | Configuration entropy of mixing | Higher                 | Lower                      |
| 9.    | Lattice distortion     | Severe                    | Mild                       |
| 10.   | Properties             | Enormous possibilities    | Limited possibilities      |
| 11.   | Atomic size mismatch   | Severe                    | Mild                       |
| 12.   | Microstructure         | More diversified          | Less diversified           |
| 13.   | Solid solution strengthening | Stronger                  | weaker                     |
| 14.   | Diffusion              | Sluggish                  | Relatively fast            |

Figure 3. The progress of research articles pertaining to the synthesis of HEAs via MA.

Table 2. Difference between conventional dilute alloys and high entropy alloys considered from different aspects.
evolution of HEAs. The detailed study discussed mechanical properties, tribological behavior, and functional properties based on their application. Furthermore, their challenges and prospect are also discussed.

2. High entropy alloys

HEAs were firstly reported by yeh et al [59] and cantor et al [60] individually in the year 2004. However, the term ‘high entropy alloys’ was coined by yeh et al. In general, alloys consist of two to three major elements whereas, the design approach of HEAs are different from conventional alloys which are built on their composition, alloy design strategy, configurational entropy, microstructure, diffusion, properties, solid solution strengthening and different aspect discussed in table 2. In terms of content, HEAs are described as alloys containing five or more principal elements in an equiatomic ratio of up to thirteen [59, 61].

In contrary to conventional alloys, the term ‘high entropy alloys’ was coined since it was believed that random phases formed sooner than intermetallic compounds owing to the high entropy of mixing, which stabilized the phases and formed a basic crystal structure [39]. Researchers have introduced terminologies like
multi principal element alloys and compositionally complex alloys to describe this new class of materials
[13, 62, 63]. Some HEAs are classified according to their compositions and microstructures, while others are
classed according to their properties or a combination of properties and microstructure stated in table 3.

Core effects: The four core effects that distinguish HEAs from the rest of such bulk alloys [68, 69] are
responsible for their remarkable properties. The effect has an impact on HEAs’ shape, microstructure, and
desired properties. Figure 4 depicts the relation amongst the four fundamental effects and the respective
interaction with composition, microstructural and related functionalities.

The thermodynamic characteristic of alloys is acknowledged as one of the four core effects known as the high
entropy effect. The state with the least Gibbs free energy is named an equilibrium state as per the second rule of
thermodynamics [9, 68]. The sustainability of solid-solution phase development is shown to be enhanced by
high entropy. The high entropy influence is essential to prevent the development of intermetallics, that are rigid
and tough to evaluate [67]. The sluggish diffusion effect, on the other hand, hinders phase change and results in
the development of slower grain growth, finer precipitates, amorphous structure, increased creep resistance,
and higher recrystallization temperature [71]. It also improves the microstructure and morphology of HEAs while
also improving their functionality [72, 73]. In HEAs, extreme lattice distortion occurs due to the presence of
several principal elements in the alloy of the solid’s solution phase., severe lattice distortion occurs. Each atom
has a distinct sort of atom next to it, with different atomic sizes, which causes lattice stress and strain. Lattice
distortion reduces the thermal impact of significant solutions stiffening in a severely distorted lattice, allowing
for increased strength and hardness [74, 75]. Ranganathan et al [76] endorsed the cocktail effect, stating that the
cocktail effect is heavily emphasized in HEAs since at least five key elements are employed to increase the
materials’ performance. HEAs can be separated into one or more phases, depending on their composition and
processing [77]. The capacity to contribute particle morphology, individual phase characteristics, and phase
distribution leads to the properties that are obtained. Intrinsic features, collective interaction among elements,
and excessive lattice distortion all contribute to the reported traits [78, 79].

3. Mechanical alloying

Vara Lakshmi et al [80] were the first to describe the production of HEAs employing MA, having produced
nanocrystalline AlCrCuFeTiZn HEA. Following that, there has been an upsurge in the number of MA-related
research papers. There are currently just three review studies on mechanical alloyed HEAs available [81–83]. As a
result, the goal of this study is to give the most recent information on mechanically alloyed HEAs and the
mechanical, tribological, and functional properties that permit potential applications.

Milling’s primary aims are reduction in particle size, blending and mixing, and particle reconfiguration
[84, 85]. The rates of welding and fracture reach steady-state equilibrium after a certain period of milling time.
The development of supersaturated solid solutions and the homogeneous dispersion of the strengthening process is required by this methodology. The welding process, which produces equiaxed particles, takes dominance in the following stage. At this point, directed welding lines have been identified; after that, the welding and fracture mechanisms have reached equilibrium, and spontaneously aligned welding lines dominate particle development. The last stage is defined by a steady-state phase wherein the microstructure refining occurs but particle distribution and sizes keep generally constant [88–90]. The MA technique is depicted in its totality in figure 5.

MA is influenced by a number of crucial factors that play an important role in the formation of uniform compounds. These variables influence ultimate product features such as final stoichiometry, degree of disorder, and, amorphization. Superior particle formation arises from improved administration of these variables. Figure 6 depicts the existing scenario of research publications dealing with MA-related variables. Table 4 further discusses different variables and their impacts on HEAs lattice strain and crystal size in detail.

3.1. Key findings

- The best approach for creating nano-structured alloys with greater chemical uniformity.
- MA features comprise shortened time, decreased power intakes, improved coating adherence, and greater versatility in the formation of diverse functional coatings [92].
- It improves configurational consistency and can effectively alleviate the segregation challenges.
- It has a better rate of diffusion and is perfectly suited for developing various kinds of materials, such as quasicrystalline, amorphous, and oxide permeation reinforced materials, among others [93].

3.2. Phase evolution in HEAs

Some of the central themes of extensive study in HEAs include phase stability and their evolution [91, 130]. The primary factor that permits the development of the crystalline phase in HEAs is the configurational entropy [80]. The \( \Delta \text{Sconf} \) effect is established on the second rule of thermodynamics for an irreversible process that proceeds exclusively in a single path for a minimum free energy state depicted by

Some of the core aspects of extensive investigation in HEAs entail phase development and sustainability [87, 118]. The main determinant that facilitates the development of solid crystalline phases in HEAs is configurational entropy [80]. For the irreversible process that only advances in one way for a comparatively lower energy state indicated by the \( \Delta \text{Sconf} \) effect.

\[
\Delta G_{\text{mix}} = \Delta H_{\text{mix}} - T \Delta S_{\text{mix}}
\]

Where \( \Delta H_{\text{mix}} \) is the enthalpy of mixing, \( \Delta G_{\text{mix}} \) is Gibbs free energy and \( \Delta S_{\text{mix}} \) denotes the entropy of mixing, that is described in the given expression.
Table 4. HEAs synthesized through MA technique: particle size, process parameters, and their response on outcomes.

| S. no. | HEA powder                  | Feed stock | Milling parameters | Phases References |
|--------|-----------------------------|------------|-------------------|-------------------|
| 1.     | AlCoCrCuFeTi x              | —          | 45                | 10:1              | 0.096–0.231 bcc + fcc [94] |
| 2.     | Al xCoCrCuFeNiTi x          | 99.60      | 30                | 10:1              | 0.175 bcc + fcc [95] |
| 3.     | AlCrFeTiCuZn x              | 99.50      | 45                | 10:1              | 1.31–1.52 bcc + fcc [80] |
| 4.     | CuCoFeNi x                  | 99.50      | —                 | 10:1              | 0.73 FCC [96] |
| 5.     | Co xCrFeNi 3Ti x            | 99.50      | —                 | 10:1              | — bcc [97] |
| 6.     | CoCrMnFeNiTi x, C x         | 99.50      | —                 | 15:1              | — bcc + fcc [92] |
| 7.     | CoNiTiFe x                  | 99.90      | 50                | 25:1              | 1.5 6.55 bcc + fcc [98] |
| 8.     | AlCoFeNi x                  | 99.00      | —                 | 5:1               | — 7.1 bcc + fcc [99] |
| 9.     | AlFeCrMo x                  | 99.50      | —                 | 10:1              | — bcc [100] |
| 10.    | AlCoNiFeMo x                | 99.00      | —                 | 5:1               | 8.3–16.5 bcc [99] |
| 11.    | CoCrNiFe x                  | 99.90      | 10                | 25:1              | 1.4 bcc + fcc [102] |
| 12.    | AlNiTiCoZr x                | 99.50      | 70                | 15:1              | — Amorphous [101] |
| 13.    | NbMoWV x                    | 99.50      | 50                | 10:1              | 0.58 11 bcc + fcc [102] |
| 14.    | CoCrNiFe x                  | 99.50      | —                 | 10:1              | — 10 bcc + fcc [103] |
| 15.    | AlCr xCoNiFe x, C x         | 99.50      | 180               | 15:1              | — bcc + fcc [104] |
| 16.    | AlCoCrFeNi x, Ti x          | 99.00      | —                 | 5:1               | — 6.8 bcc + fcc [99] |
| 17.    | CoCrFeNiMn x                | 99.90      | 45                | 25:1              | — fcc [105] |
| 18.    | NbTaWMo x                   | 99.90      | 48                | 300               | 10:1 0.688 11.8 bcc [26] |
| 19.    | CoCrCuFeNi x                | 99.50      | —                 | 15:1              | 1 7 bcc + fcc [96] |
| 20.    | CoCrFeNi x                  | 99.50      | —                 | 15:1              | 0.83 6 bcc + fcc [96] |
| 21.    | CrCuFeTiZn x, Pb x          | 99.50      | 44                | 200               | 20:1 0.037–0.1092 — bcc + fcc [105] |
| 22.    | (CrCuFeTiZn) x, Pb x        | 99.50      | —                 | 20:1              | 0.037–0.1092 — bcc + fcc + Pb [105] |
| 23.    | NbMoTaW x                   | 99.50      | 75                | 6                  | 300 10:1 0.96 66.1 bcc + fcc + Pb [106] |
| 24.    | Fe xNi23Co23Cr23Mo23WNb23C2 | 99.50      | 75                | 940               | 60:1 — — Mo + γ [107] |
| 25.    | NbMoTaWTi x                 | 99.90      | —                 | 13:1              | — — bcc [108] |
| 26.    | CoCrFeMnNi x                | 99.90      | 300               | 1100              | 10:1 — 11 fcc [109] |
| 27.    | FeCoMnNiV x                 | 99.90      | 20                | 350               | 10:1 — — bcc + fcc [110] |
| 28.    | AlCrCuNiFe x                | 99.80      | —                 | 5                  | 380 10:1 0.2893–0.2889 14 bcc [111] |
| 29.    | FeCrCuNiMn x                | 99.90      | 45                | 250               | 15:1 11.4 fcc + bcc + γ + Cr23C6 [112] |
| 30.    | FeCrNiMoV x                 | 99.50      | 45                | 200               | 10:1 1.06 40 bcc [113] |
| 31.    | MoNiTiTaV x                 | 99.90      | 48                | 350               | 10:1 0.89 12.9 bcc [114] |
| 32.    | WMoCrVTa x                  | 99.50      | —                 | 32                | 250 6:1 — 3.1586 bcc [115] |
| 33.    | CoCrNiZnCu x                | 99.50      | 45                | 6                  | 300 20:1 0.70 13 bcc [116] |
| 34.    | AlFeCoCrNiSi x              | 99.50      | —                 | 20                | 300 10:1 0.87 32 bcc [117] |
\[ \Delta S_{\text{mix}} = \Delta S_{\text{config}} + \Delta S_{\text{thermal}} \]  

(2)

It is evident from the following equation that when \( \Delta S_{\text{mix}} \) increases, the free energy of solid solutions diminishes.

According to Boltzmann’s analysis, \( \Delta S_{\text{config}} \) can be calculated from the given expression,

\[ \Delta S_{\text{config}} = -R \sum_{i=1}^{n} X_i \ln X_i \]  

(3)

Where \( R \) denotes the universal gas constant and \( X_i \) denotes the mole fraction,

\[ \text{for } X_i = \frac{1}{n} \]  

(4)

\[ \Delta S_{\text{config}} (\text{max}) = R \ln n \]  

(5)

The number of elements is denoted by \( n \). \( \Delta S_{\text{config}} \) is not an adequate factor to preserve the solid solution; key determinants must be considered to determine the solid solution formation criteria. According to Zhang et al [119], definite criteria must be fulfilled in the quest for a solid solution to emerge that depicted in figure 7.

MA is an effective approach for HEAs to achieve improved performance by altering microstructure and phases. Elements like Cu, Co, Ni, and Mn encourage the growth of the FCC phase, whereas Al, V, Cr, and Ti promote the advent of the BCC phase [120]. Al is important for controlling phase forming and influencing mechanical, thermal, and tribological aspects [57]. Chung et al investigated AlxCoCuNiFe (\( x = 0 \) and 0.3) HEAs and found that as the Al content increased, the BCC phase became more prevalent, resulting in better hardness. In a similar study, Al was evidenced to be a BCC stabiliser and a solid solution hardening agent [121]. The alloying behavior of distinct HEA elements is accomplished during milling.

Rituraj chandrakar et al [49] discussed the effect of Si content on phase evolution of AlCoCrCuFeNiSi. Figure 8(i) XRD pattern proved that the BCC is a prominent phase in comparison to FCC owing to the lesser value of VEC. The mixing enthalpy becomes more negative with the addition of Si which is also favorable for the formation of BCC phase. With the milling time, peaks get broadened which indicated the refinement of crystal size, increase in lattice strain, and the solid solution evolution. Figure 8(ii) demonstrated the SEM micrograph of the AlCoCrCuFeNiSi, HEAs figure 8(iii) shows the EDS spectrum of the region. With the addition of Si, large volume fraction of BCC is observed in which BCC phase is in rich Fe–Al–Si elements whereas sigma phase is rich in Cr element.

Guofeng wang et al [114] examined the influence of milling duration on MoNbTaTiV HEA and found that lattice strain increases while grain size decreases as milling time increases. Furthermore, the milling time XRD pattern showed that Ti and V peaks disappeared after milling time of 5 h and 15 h. However, after 20 h of milling, nearly all of the peaks were disappeared. Elements with a higher melting point seem to have a lower diffusion coefficient and vice versa. Figure 9 depicts the dissolution sequence of MoNbTaTiV.

Mohanty et al [122] discussed the microstructure of equiatomic AlCoCrFeNi HEA where the XRD pattern obtained in figure 1(a) revealed that FCC and BCC solid solution formed in which fcc is predominant peak. Figure 10(b) SEM micrograph shows two phases contrast which indicated the presence of two-phase in MA HEA powder. In figure 10(c) TEM micrograph showed the grain of the HEA particle for 25 h milling figure 10(d) confirm the nature of the particle by SAD of fcc solid solution whereas figure 10(e) represented the SAD of another particle which indexed due to bcc solid solution.

3.3. Various attributes of mechanical alloying

Achieving fine particles having specified morphology and microstructure is a difficult task. This can be accomplished while optimization of process variables. The following are the process variables and their impact on MA:

3.3.1. Ball to powder weight ratio (BPR)

The degree of amorphization is significantly influenced by the kinetic energy of the ball milling, resulting in reaction and interdiffusion. The amorphization rate rises as BPR rises. The amorphous phase proportion is noticed in the first 48 h of ball milling, and subsequently, as the heat produced rises, a crystalline phase is found. Small particles are produced at a higher BPR, thus, the use of a high weight ratio has a drawback in the form of contamination [123]. However, at lower BPR, the volume of the crystallites fluctuated, suggesting a change in the efficacy of the milling operation & insufficient phase development [124].

3.3.2. Rotational speed

Rotational speed has an impact on particle shape as well. The ball strikes the ball or container surface with significant force at greater speeds, which favors welding. The particle size rose as the rotational speed grew. The maximum impact energy is obtained at higher RPMs, however, it is observed that milling time efficiency is shown to be low at lower speeds [125]. Ciprian et al [19] produced HfNbTiTaZr HEAs & explored how rotating...
speed affects them. They observed that the ideal crystallite size was achieved at 300 RPM when the RPM was controlled between 200 and 300. Khailo et al. [126] pioneered the notion of high-intensity MA in the synthesis of HEAs. A single-phase FCC CoCrNiFe HEAs is developed in 2 h, whereas typical milling takes about 10 h. According to Salemi et al. [127], suitable alloying was not accomplished after 50 h of milling time & a rotating speed of 300 RPM.

Single-phase FCC was achieved when the rotating speed was raised to 350 RPM. This is stated that with a rise in rotating speed, transfer of energy to the HEA metallic powder is predicted to be enhanced nearly by 1.7 times (at approx. 350 RPM). Tan et al. [128] produced Al$_2$NbTi$_3$V$_2$Zr at 350 and 150 RPM, respectively. High-energy milling was shown to be significantly better efficacious compared to low-energy MA.

### 3.3.3. Milling time

The fracture cold-welding process occurred during milling. Cold-welding prevails over fracturing in the early stages of milling, resulting in a dramatic rise in particle size, accompanied by a reduction in particle size once the fracturing process gets hold. An XRD pattern at various milling durations can be used to evaluate the level of alloying [114]. Figure 11 depicts the influence of milling time on the microstructure and morphology of HEAs.

---

**Solid solution formation criterion for HEAs**

| Entropy of Mixing | $\Delta S_{\text{config}} > 1.61 R$ |
|-------------------|-----------------------------------|
| Enthalpy of Mixing | $-15 KJ/mol < \Delta H_{\text{mix}} < 5 KJ/mol$ |
| Size Factor       | $\delta < 6.6\%$ |

**Figure 7.** Criterion for the emergence of solid solution HEAs.

**Figure 8.** (i) XRD pattern of (a) AlCoCrCuFeNi and (b) AlCoCrCuFeNiSi$_{10.9}$ HEAs for varying milling time, (ii) SEM micrograph of AlCoCrCuFeNiSi$_{10.9}$ HEAs and (iii) EDS analysis of AlCoCrCuFeNiSi$_{10.9}$ HEAs [49].

---

---

---
after a particular period of time when cold welding and fracturing are in balance. Furthermore, the milling period should not be excessively long because longer milling times diminish diffraction peaks. This suggests that a prolonged milling duration has a detrimental effect on phase recognition of the powder. It’s also been discovered that when milling duration goes up, the crystal size reduces, and lattice strain rises\cite{86}. The extreme plastic deformation of HEA particles in milling is attributable to structural imperfections including dislocation motion and deficiencies, which result in increased lattice strain\cite{129}. Undesired phases and impurity concerns might emerge when milling time is extended\cite{130}. Milling is undesirable and fails to obtain acceptable attributes at shorter milling durations\cite{65}. Table 5 shows the influence of milling time affecting the desirable attributes of HEAs specifically.

3.3.4. Process control agent (PCA)
Maintaining particle shape and size is usually a difficult job, and milling environments are vital\cite{139, 140}. Surface-active materials, usually referred to as process control agents\cite{141}, are one of the measures being used to prevent severe welding. These PCA get deposited on the particles’ surfaces and significantly lower surface tension\cite{142}, limit agglomeration, and interfere with cold welding. Toluene, methanol, stearic acid, ethyl
alcohol, and propyl glycol, are common control agents described in MA [143]. PCA alters the inherent character of materials by interacting with surface particles, affecting dissolving degrees, refining crystal size, and influencing ultimate mechanical behavior [144].

3.3.5. Ambient conditions
The milling ambient circumstances are among the most important aspects that influence compositional metallic powder [145]. While milling, a very finer powdered particle with a high specific surface area is formed, which is extremely reactive with oxygen and forms oxidised compound, as well as other gases such as H₂, N₂ or, S, etc [77].

3.3.6. Summary and parameters recommendations of MA
The operational parameters must be tailored to obtain the utmost possible properties. In MA, the spherical morphology of elemental powder progressively evolves depending on several factors including a low ball to powder ratio (10:1) and a medium speed of 300 RPM during the optimal duration that can considerably retain the morphology of alloyed particles [146–148]. Milling duration must not be quite long; longer milling times diminish diffraction peaks. This reveals that a prolonged milling duration has a detrimental impact on phase characterization and identification of the material. Stearic acid is the most suited surface-active material in the MA consistent fracturing-welding process to achieve an appropriate balance amid fracturing & welding. Yating Qiao et al [149] noticed that refractory metals cause extreme cold welding during MA in the Solid PCA (stearic acid), and absence of PCA, whereas the presence of liquid PCA efficaciously relieved the cold welding, raising the recovery proportion from 5% to 90% by limiting direct contact between metal powder and metal powder. The attributes with varied ranges and suggested values are detailed in table 6 derived from the prior discussion.

4. Characteristics and applications

4.1. Mechanical characteristics
Mechanical characteristics are the main significant deciding aspect in terms of material performance and durability, and phases play a prominent part. FCC-based HEAs, for example, have a low yield strength but great plasticity, while BCC has a high yield strength but poor plasticity. The microhardness of mechanically alloyed HEAs varied between 375 and 699 HV. The advantage of MA accompanied by various consolidation processes was the formation of nano-twins, precipitates, and numerous hardening mechanisms, all of which improved the strength of HEAs. The hardness of CoCrFeNi treated with MA and SPS is 570 HV [150], which is approximately four times that of the as-cast alloy (150 HV) [151]. The compressive strength of AlCrCoFeNi synthesized by MA and SPS was 2.6 GPa [122], which was approximately twice that of as-cast HEA [152]. When AlCoFeMoNiTi HEA was processed via MA, nanoprecipitates were produced that had better strength over as-cast HEAs [134].

Figure 11. Characterization of MoNbTaTiV HEA milled powder (a) particle size distribution (b) average particle size (c) cross-section HEA SEM images. Reproduced from [114], with permission from Elsevier.
| S. No. | HEA                                      | Milling time             | Remarks                                                                 | References |
|-------|------------------------------------------|--------------------------|-------------------------------------------------------------------------|------------|
| 1.    | Varying Al0.3CrFe1.5MnNi0.5, Al0.5CrFe1.5MnNi0.5 | 10 min, 5 h, 10 h, 15 h, 20 h | • As the milling time advances, the average crystallite size reduces and thus the lattice strain raises. For Al0.3CrFe1.5MnNi0.5, Minimum crystal size and maximum lattice strain is observed at 15 h whereas for Al0.5CrFe1.5MnNi0.5 it reached 20 h. | [131]      |
| 2.    | CoCrMnFeNiTi0.1                           | 10 h, 15 h, 20 h         | • At a 20 h milling duration, hardness & yield strength enhanced by 20% and 33%, respectively. | [132]      |
| 3.    | AlCrCuFeNi                                | 0 h, 10 h, 20 h, 30 h, 40 h, 50 h, and 60 h | • A dual-phase (BCC + FCC) AlCrCuFeNi was obtained via the MA processing route. | [129]      |
| 4.    | AlCrCuZnFe                                | 2.5 h, 10 h, 20 h, 40 h  | • AlCrFe and CuZn, two remarkably irregular and saturated solid solution phases, have been identified. | [133]      |
| 5.    | AlCoFeNiMoTi                              | 10 h, 20 h               | • The AlCrFe BCC had the maximum hardness, which was 661 Hv. | [134]      |
| 7.    | AlCoCrNiFe                               | 10 h, 20 h, 30 h         | • Improved yield strength, higher hardness, and outstanding magnetic characteristics. | [93]       |
| 8.    | CoCrMnFeNi                               | 20 min, 60 min           | • Potentially contaminated with zirconia pellets, ZrO2 peaks were found. | [109]      |
| 9.    | FeCoVNiMn                                | 0, 48 h, 72 h, 96 h      | • As the milling duration approaches 72 h, the composition of the major phases near stoichiometry, and the phase separation becomes increasingly noticeable. | [110]      |
| 10.   | AlCoNiFeCr                               | 1 h, 2 h, 3 h, 4 h & 5 h | • After 5 h of milling, a unified super-saturated solution containing bcc phase was obtained. | [111]      |
| 11.   | AlFeCrNiCo                               | 5 h, 10 h, 15 h, 20 h    | • The corrosion performance of HEAs is influenced by stepwise alloying. | [115]      |
| 12.   | Fixed Milling Time FeCuCoNi_{x}Y_{0.2}   | 60 h                     | • Boron imparts greater hardness and superior strength, whilst still permitting ductility and mild magnetism. | [55]       |
| 13.   | AlCrCoFeNi                               | 28 h                     | • Milling followed sintering reduces the time needed for undesired phases and contaminants to occur by controlling the emergence of contaminants and unwanted phases. | [136]      |
| 14.   | AlCrCoFeNi                               | 4 h                      | • It was able to reach higher tensile strength & strain as well as better wear resistance & anti-adhesive characteristics. | [137]      |
| 15.   | AlFeCoNiCr_{x}                           | 90 h                     | • Its high thermal resistance, mild magnetic characteristic, and resistance against corrosion made it a viable radiation absorbing material. | [138]      |
The compressive yield strength and ductility of NbMoTaW HEA produced using MA and SPS reported as 2612 MPa and 8.8% of NbMoTaW HEA produced using MA and SPS. Similar HEAs were produced by arc melting in another study, with ductility and strength of 1.7% and 1246 MPa, respectively [153].

Mechanical properties of non-equatomic Co1.5 FeCrNi1.5Ti0.5 HEAs prepared by MA and SPS were studied, and bend strength of 2600 MPa, a tensile strength of 1400 MPa, hardness of 4400 MPa, and ductility of 4% was found, those were significantly superior to typically as-casted HEA [97]. A substantial FCC phase was generated in an AlCoNiFeTi HEA processed by MA and SPS, along with B2 phase precipitates and Al1.5Ti particles. The inclusion of TiO2 particles and Ni3Ti precipitates in the FCC phase of Co1.5CrFeNi1.5Ti0.5 resulted in a superior combination of 1460 MPa strength and 14.5 percent ductility [154]. Al7.5Fe25Co25Cu17.5Ni HEA exhibited higher hardness (454 HV) and superior strength (1795 MPa) [155]. Furthermore, various HEAs were processed through MA and different processing techniques listed in table 7.

### 4.2. Tribological characteristics

It is challenging to develop a high wear-resistant material without compromising mechanical properties such as compressive and tensile strength [172]. However, HEAs present a novel design approach to develop a material with exceptional tribological properties as well as good mechanical properties, a proper balancing between alloy matrix and self-solid lubricating element or hard particles must be established. The HEA solid solution achieved with exceptional tribological properties as well as good mechanical properties, a proper balancing between alloy matrix and self-solid lubricating element or hard particles must be established. The HEA solid solution achieved significant chemical disorder and topological order, overcoming the strength-ductility trade-off unconventionally [45].

The coefficient of friction (COF) and rate of wear is used to assess the tribological behaviour of materials. Three configurations, namely block on block, ball on disc, and pin on disc were employed to evaluate the tribological behaviour of newly designed HEAs [173]. Various aspects such as applied load, rotation speed of the disc, and time or total distance impact the wear rate in the methods described above. Although the majority of HEA research is focused on structural properties, tribological behavior research has lately garnered attention. Cantor alloys have been extensively studied for their tribological properties; revealing the intrinsic wear characteristics of cantor alloys is critical. Nagarjuna et al [174] examined the wear behaviour of CoCrFeMnNi HEA utilizing a ball on disc. The surface of the HEAs was scratched with some adherent debris at the start of the wear testing, as shown in figure 12. When the applied load rises, the stress at the contact surfaces increases, causing surface cracking and delamination. So, the result indicated that the transition occurred from adhesive and abrasive wear to delamination as the duration of wear is continued and examined the variation of CoF with rate of wear is used to assess the tribological behaviour of materials. Three configurations, namely block on block, ball on disc, and pin on disc were employed to evaluate the tribological behaviour of newly designed HEAs [173]. Various aspects such as applied load, rotation speed of the disc, and time or total distance impact the wear rate in the methods described above. Although the majority of HEA research is focused on structural properties, tribological behavior research has lately garnered attention. Cantor alloys have been extensively studied for their tribological properties; revealing the intrinsic wear characteristics of cantor alloys is critical. Nagarjuna et al [174] examined the wear behaviour of CoCrFeMnNi HEA utilizing a ball on disc. The surface of the HEAs was scratched with some adherent debris at the start of the wear testing, as shown in figure 12. When the applied load rises, the stress at the contact surfaces increases, causing surface cracking and delamination. So, the result indicated that the transition occurred from adhesive and abrasive wear to delamination as the duration of wear is continued and examined the variation of CoF with

### Table 6. Preferred Values for processing parameters in MA.

| S. No. | Process variables               | Variable range | Refractory HEAs | Transitional metal HEAs |
|-------|---------------------------------|----------------|----------------|-------------------------|
| 1.    | Particle size (μm)              | 20–300         | 60             | 40                      |
| 2.    | Process control agent (PCA)     | ethyl glycol, ethanol, Methanol, ethanol, ethyl propyl alcohol n-heptane, stearic acid, toluene | n-heptane | Stearic acid |
| 3.    | PCA Concentration (wt%)         | 1–5            | 2.5            | 1.5                     |
| 4.    | Ball to powder weight proportion | 6:1–60:1       | 15:1           | 10:1                    |
| 5.    | Rotational speed (RPM)          | 200–1200       | 400            | 300                     |
| 6.    | Milling time (h)                | 6–90           | 55             | 42                      |
| 7.    | Environmental conditions         | Vacuum, argon, helium, nitrogen, and atmospheric condition | Argon | Argon |

The compressive yield strength and ductility of NbMoTaW HEA produced using MA and SPS reported as 2612 MPa and 8.8% of NbMoTaW HEA produced using MA and SPS. Similar HEAs were produced by arc melting in another study, with ductility and strength of 1.7% and 1246 MPa, respectively [153].
Table 7. Summarizes the key deliverables of several HEAs produced using different processes.

| S. No. | HEA | Processing technique | Tensile strength | Compressive strength | Hardness | Plasticity Strain | References |
|--------|-----|----------------------|------------------|----------------------|----------|-------------------|------------|
|        |     |                      | UTS (MPa) | SyT (MPa) | UCS (MPa) | SyC (MPa) |                      |            |
| 1.     | CrFeMnCoNi | MA + SPS | — | — | 1907 | — | 625 Hv | 11.16 εc | [156] |
| 2.     | Ni0.5Co1.5FeCrTi0.5 | MA + SPS | 1384 | 1308 | — | — | 442 Hv | 4.01 εT | [97] |
| 3.     | CrFeMnCoNi | MA + HIP | — | — | 2000 | 1900 | 699 ± 14 | 0.5 εT | [51] |
| 4.     | FeCrNiCo1.5Al0.7 | MA + SPS | — | — | 2635 ± 55 | 2033 ± 41 | 624 ± 26 Hv | 8.12 ± 0.51 εc | [157] |
| 5.     | (FeCoCrNi)Al0.75Cr0.25 | MA + VAM | — | — | 2787 | 859 | 375 HV | 43.6 εc | [158] |
| 6.     | (FeCoCrNi)Al0.75Cr0.25 + 10vol%TiC | — | — | — | — | — | — | — | — |
| 7.     | CrCoMnFeNi | MA + SPS | 1055 | — | — | — | 526 Hv | 6.3 εT | [159] |
| 8.     | FeCrCoNi | PM | 712.5 | 359 | — | — | — | 56 εT | [160] |
| 9.     | Al0.5CoCrNiFe | Arc Melting | 1406 | 1292 | — | — | 399 Hv | 6 εT | [161] |
| 10.    | CrCoFeMnNi-C | Arc melting | 1616 | 527 | — | — | — | 1.84 εT | [162] |
| 11.    | CoFeNiCrAl | Arc Melting | — | — | 2004.23 | 1250.96 | — | 32.7 εc | [163] |
| 12.    | Al0.5CoCrFeNiMo0.3 | Arc Melting | 2117 | 1091 | — | — | 571 Hv | 18 εT | [164] |
| 13.    | AlCoNiFeAl0.4Ti0.6Cr0.5 | MA + HPS | 362 | 336.2 | — | — | 15.2 GPa | 8.4 εT | [165] |
| 14.    | NbMoTaTiV | VAM | — | — | 2450 | 1400 | 443 Hv | 30 εc | [166] |
| 15.    | FeCrCoNiMnAl0 | MA + HPS | — | — | 2026 | 1314 | 415 Hv | 20.3 εc | [167] |
| 16.    | FeCrCoNiMnAl0.1 | — | — | — | 2086 | 1631 | 432 Hv | 12.6 εc | [167] |
| 17.    | FeCrCoNiMnAl0.3 | — | — | — | 2341 | 1836 | 511 Hv | 4.9 εc | [167] |
| 18.    | FeCrCoNiMnAl0.5 | — | — | — | 2376 | 1932 | 553 Hv | 3.8 εc | [167] |
| 19.    | FeCrCoNiMnAl0.7 | — | — | — | 2552 | 2230 | 622 Hv | 1.69 εc | — |
| 20.    | Al0.2CoCrFeNi | Arc Melting | 736 | 691 | — | — | 401.3 Hv | 12.5 εT | [168] |
| 21.    | AlFeCoNiCrMn | MA + SPS | 1011 | — | — | — | 3.7 GPa | — | [169] |
| 22.    | Nb25Ta25Mo25W25 | MA + SPS | — | — | 3016 | 2460 | 7.8 GPa | 16.8 εc | [170] |
| 23.    | Ti23Nb25Ta25Mo25W23 | MA + SPS | — | — | 3340 | 2377 | 7.35 GPa | 26.3 εc | — |
| 24.    | Nb25Ta25Mo25W25 | VAM | — | — | 1211 | 1058 | 4.46 GPa | 2.6 εc | — |
| 25.    | HfMoTaTiZr | VAM | — | — | — | 1600 | 123 VH | 4 εc | [171] |
| 26.    | HfMoNiTaTiZr | — | — | — | 1512 | 125 VH | 12 εc | — | — |
plastic deformation and adhesive wear, increasing wear resistance. Surface hardening, namely nitriding and boronizing, can enhance the tribological behaviour of HEAs. The thickness of the surface hardening layer protects against wear. However, researchers investigate the role of self-lubrication on the tribological behavior of HEAs. It has been found that solid lubricant plays a key role in controlling wear rate. The several kinds of solid lubricants utilized in high entropy alloys such as graphite, MoS2, BaF2, Cu, and Ag are reported. The soft phase Ag and Cu, which have low shear strength, are purportedly employed in CoCrFeNi HEA, which improves HEA wear resistance. Verma et al [180] evaluated the tribological properties of CrCoFeNiCux (x = 0 to 1, at 0.2 mean intervals) HEAs. Cu particle segregation at the grain boundaries of CrCoFeNiCux HEAs reduces wear rate at room temperature and 600 °C. The wear rate of CrCoFeNiCux HEAs bearings at higher temperature is stated to be lower than at room temperature. To achieve self-lubricating capabilities, HEAs are designed with a tailored composition that includes lubricating additives with self-lubricating properties. Kumar et al [181] carried out a wear investigation of Al0.4FeCrNiCo (x = 0, 0.25, 0.5, 1.0 M) HEAs under oil lubrication by varying the normal load, sliding distance, and sliding speed. The effect of varying Co was also carefully examined. It was stated that maximal wear was observed for Co = 1 HEA for two reasons: (i) when cobalt concentration increases, hardness decreases, and (ii) an oil film breakdown occurs. The wear surface revealed peeling off, flow material, and cracks seen perpendicular to the sliding direction. Another work used demineralized water with and without a 3.5% NaCl solution to conduct wear testing. The wear mode reported during the investigation were combined effect of adhesion with delamination, plastic flow, abrasive, and oxidation [182]. Furthermore, other articles on wear characteristics of HEAs are enlisted in table 8.

4.3. Corrosion behavior
The corrosion behavior is evaluated by electrochemical/chemical interaction between material and its surrounding. Corrosion affects the proper functioning of materials that leads to failure during its functionality corrosion. Corrosion costs more than 3% of the world’s GDP [196]. Therefore, the study of corrosion behavior has great significance. The corrosion resistance of HEAs depends on a different set of attributes that are primarily

---

**Figure 12.** (a) shows the schematic diagram of ball-on-disc while sliding in reciprocation motion, (b) illustrates the variation of average COF and (c) specific wear rates of CoCrFeMnNi HEA with increasing sliding time (1, 5, 10, 15, and 20 min), load (2, 4, 6, 8 and 10 N) and velocities (0.02, 0.05, 0.1, 0.15 and 0.2 m s⁻¹) in dry and atmospheric conditions. SEM top view shows the wear tracks with sliding time; (d) 5 min, (e) 10 min, and (f) 20 min at a constant load of 6 N and sliding velocity of 0.1 m s⁻¹. SEM cross-sectional micrographs of wear tracks examined parallel to the sliding direction specifying the extent of subsurface plastic deformation with an increase in sliding time (g) 5 min, (h) 10 min, and (i) 20 min. Reproduced from [174], with permission from Elsevier.
dependent on chemical homogeneity for elemental distribution through grain boundaries and crystalline phases. However, passive films stability plays a vital role in this aspect [197]. Figure 14 illustrates design guidelines for corrosion resistance HEAs.

The corrosion behavior of HEAs depends upon several factors such as follows:

- The impact of alloying materials
- The effect of microstructure
- Environmental stability & passivation mechanism of passive films formed on HEAs.
- Influence of processing methods on corrosion resistance.

The passive layer has a great influence on the corrosion behavior of the alloys. Shi et al [198] used XPS and electro-chemical impedance spectroscopy to explore the influence of Al on passive films of HEAs and show the corrosion process of AlxCoFeCrNi alloys in 3.5 wt% NaCl. The passive layer on the surface of the AlxCoFeCrNi alloy reduced even as the concentration of Al rose, whereas the passive layer on the surface dropped as the Cr concentration grew. The overall composition of the passive coating on the surface of stainless steel is closely linked to its corrosion resistance, with Cr oxide playing the most important role [199]. The concentration of Cr above 12% ensures passivation. Cr is commonly utilized as one of the key elements of high-performance alloys (HEAs) that improve corrosion resistance. Chai et al [200] investigated the effect of Cr concentration on the resistance to corrosion of FeCoNiCrX alloys exhibiting fcc phase in 3.5 wt% NaCl and 0.5 M H2SO4 in 3.5 wt percent NaCl and 0.5 M H2SO4, respectively. The columnar structure of the FeCoNiCr0.5 alloy was preserved in both treatments, but the passive area and breakage potential of the alloy increased dramatically. Shi et al [201] shown that a decrease in short-range elemental segregation and a variation in phase composition might have a substantial impact on the corrosion rate of AlxCrCoFeNi (x = 0.3, 0.5, 0.7) HEAs. After a 1000 h treatment at 1250 °C, the grain size of the Al0.5CrCoFeNi alloy increased to five times that of the as-forged state; also, some annealing twins emerged. The work function of the as-equilibrated Al0.5CoCrFeNi alloy was increased by 50 meV due to the decrease in imperfections and short–range elemental segregation of HEA during high-temperature homogenization, implying that the Al0.5CrCoFeNi alloy has greater corrosion resistance (figures [15](a) and (b)). The disordered Cr-Co-Fe-rich BCC phase solubilized into the Al-Ni-rich B2 matrix over the same thermal processing in the Al0.5CrCoFeNi alloy, lowering the composition distinction in between BCC.
Table 8. Summary of literature results on wear rate and friction, processed via different synthesis routes whereas the main focus is on mechanical alloying.

| S.No. | HEAs                         | Synthesis technique | Testing method | Ball/pin dia/ | Load (N) | Distance/time | Speed | Ambient conditions | Hardness | Wear rate | COF | References |
|-------|------------------------------|---------------------|----------------|---------------|----------|---------------|--------|-------------------|----------|-----------|-----|------------|
| 1.    | (CuCrFeTiZn)₁₀₀₋ₓPbx        | MA + SPS            | Ball on disk   | 4             | 7        | 400 s         | 0.41 m s⁻¹ | RT                | 3.5–6 GPa | 1.17 × 10⁻¹⁴ | 0.28 | [173]      |
| 2.    | CoCrFeNiCu                  | MA + HPS            | Ring-disk      | 10 x 17 x 20  | 1000     | 900 s         | 100 rpm | ET                | 450 HV   | —         | 0.6 | [183]      |
| 3.    | Al₂Mo₂NiFeTiMn₂              | MA                  | Reciprocating wear tester | 6             | 50       | 1800 s        | 200 rpm | RT                | 1098 HV  | —         | 0.41 | [184]      |
| 4.    | Fe₁.₄CoCrNi                 | MA + SPS            | Pin on disk    | 3             | 10       | 1000 m        | 0.2 m s⁻¹ | RT                | 320–400  | 0.02% weight loss | 0.65 | [185]      |
| 5.    | CoCrFeNi₁₋ₓMo+0.5            | MA + HPS            | Ring on disk   | 10 x 17 x 20  | 100      | 900 s         | 100 rpm | ET                | 600 HV   | 5 mg      | —   | [186]      |
| 6.    | NiCoCrFeZr₁₋ₓCu             | MA + SPS            | Pin on disk    | —             | 5        | 1000 m        | 0.2 m s⁻¹ | RT                | 845 HV   | 0.001 mg m⁻¹ | 0.7 | [187]      |
| 7.    | CoCrFeMnNi                  | MA + SPS            | Ball on disk   | 6             | 15       | 1000 m        | 100 mm s⁻¹ | RT                | 640 HV   | .0096     | 0.7 | [188]      |
| 8.    | CoCrFeNi(WC)                | MA + HPS            | Pin on disk    | 10 x 17 x 20  | 100      | 900 s         | 100 rpm | ET                | 531 HV   | —         | 0.3 | [189]      |
| 9.    | AlFeTiCrZnCu                | MA + VHP            | Pin on disk    | 10            | 30       | 1600 m        | —       | RT                | 9.5 GPa  | 0.01 gm   | —   | [28]       |
| 10.   | CoCrFeNiM₀₂₋ₓMo             | MA + SPS            | Ball on disk   | 6.35          | 20       | 36 m          | 6 mm s⁻¹ | RT                | 460 HV   | —         | 0.629 | [190]      |
| 11.   | CuZrAlTiNi                  | MA + VHP            | Pin on disk    | —             | 30       | 1200 m        | 200 rpm | RT                | 943 HV   | —         | 0.7  | [101]      |
| 12.   | AlCoCrFeNiSi                | MA + APS            | Ball on disk   | 5             | 5        | 1800 s        | 573 rpm | RT                | 612 HV   | (0.38±0.08 × 10⁻¹⁴) | 0.57 | [22]       |
| 13.   | AlCoCrFeNi                  | MA + SPS            | Pin on disk    | 5             | 5        | 1800 s        | 0.19 m s⁻¹ | RT                | 630 HV   | 1.9 × 10⁻⁵  | 0.57 | [137]      |
|       |                              |                     |                |               |          |               |        |                   | 200      | 560 HV    | 0.53 |            |
|       |                              |                     |                |               |          |               |        |                   | 400      | 510 HV    | 0.61 |            |
|       |                              |                     |                |               |          |               |        |                   | 600      | 490 HV    | 0.54 |            |
|       |                              |                     |                |               |          |               |        |                   | 800      | 440 HV    | 0.86 |            |
| 14.   | TiN₀₂₉CrMo                  | MA + Laser          | Ball on disk   | 3             | 4        | 3000 s        | 200 rpm | RT                | 410 HV   | 1.2 mg    | 0.45 | [191]      |
| 15.   | CoCrCuFeNiM₀₂₋ₓMo           | MA + SPS            | Pin on disk    | 5             | 15       | 1000 m        | —       | RT                | 530 HV   | —         | 0.65 | [192]      |
| 16.   | FeCoNiCu₀₂₋ₓMo              | Vacuum arc melting  | Ball on disk   | —             | —        | 3000 s        | —       | RT                | 290 HV   | —         | 0.237 | [193]      |
| 17.   | Hf₂₉Co₂₅W₂Zr                | Vacuum arc melting  | Pin on disk    | 3             | 50       | 190 m         | 5 HZ    | RT                | 6.8 GPa  | 3.1 × 10⁻⁴  | 0.26 | [194]      |
|       |                              |                     |                |               |          |               |        |                   | 423 K    | 6.3 GPa   | 7.1 × 10⁻⁴  | 0.25 |            |
|       |                              |                     |                |               |          |               |        |                   | 573 K    | 6.3 GPa   | 2.8 × 10⁻⁴  | 0.23 |            |
|       |                              |                     |                |               |          |               |        |                   | 723 K    | 6.2 GPa   | 2.8 × 10⁻⁴  | 0.21 |            |
| 18.   | Ta₄₉Ti₅WµZr                  | Vacuum arc melting  | Reciprocating wear tester | 3             | 4        | 3000 s        | 200 rpm | RT                | 8.1 GPa  | 2.8 × 10⁻⁴  | 0.23 |            |
|       |                              |                     |                |               |          |               |        |                   | 423 K    | 8.0 GPa   | 8 × 10⁻⁴   | 0.34 |            |
|       |                              |                     |                |               |          |               |        |                   | 573 K    | 7.5 GPa   | 1.1 × 10⁻⁴  | 0.32 |            |
|       |                              |                     |                |               |          |               |        |                   | 723 K    | 7.1 GPa   | 1.1 × 10⁻⁴  | 0.3  |            |
| 19.   | AlCrFeNiCu                  | Laser metal deposition technique | Ball on disk | 5             | 480 s    | Operating power 2200 W | | RT | 350 HV | 0.01 g | 0.28 | [195] |
| S.No. | HEAs Synthesis technique | Testing method | Ball/pin dia./Load(N) | Distance/time | Speed | Ambient conditions | Hardness | Wear rate | COF | References |
|-------|--------------------------|----------------|----------------------|---------------|-------|--------------------|----------|-----------|-----|------------|
| 2000 W | 0.01 g 0.27 | 1800 W 0.01 g 0.34 | 1600 W 0.02 g 0.33 |  | |  | 1600 W | 0.27 | 0.24 | 0.28 | A Kumar et al. |

Table 8. (Continued.)
and FCC phases and thereby lessening potential gradients across the interphase (figure 15(e)). Ultimately, when referred to the as-forged $A_{0.7}CrCoFeNi$ alloy, the volume fraction of the Cr-Co-Fe-rich bcc phase in the as-equilibrated $A_{0.7}CrCoFeNi$ alloy lowered from 45% to 22%, along with the microstructural modification of the Cr-Co-Fe-rich BCC phase from mesh-like to block-like, resulting in a substantial decrease in the potential difference among different microstructures figures 15(f)–(h).

4.4. Functional properties
HEAs are novel designed materials that are being studied for their microstructure and mechanical characteristics. There has been some progress in the study of the functional characteristics of HEAs. Soft magnetic properties, resistance against Irradiation, catalytic properties, and thermoelectric capabilities are all included in table 9. Their specific structural property, multi-principal element solid solution, has an impact on these characteristics. In applications such as Automotive industries, Nuclear irradiation components, solar plates, and energy sectors possess functional characteristics that are very critical.

4.5. Potential applications
In addition to the commonly used superalloys, the need for structural and functional materials is surging in various sectors, including extraction, railway, mining [229], defense [230], and aviation in science and engineering. Figure 16 depicts the existing and anticipated uses of various HEAs in various industries.

1. $Ti_{15}V_3Cr_3Sn_3Al$ HEAs are employed as embedded aircraft equipment with their exceptional strength ratio and outstanding cold formability [231]. $Ti_{10}Al_8V_6Cr_2Zr_2Mo$, on the other hand, has a foothold in the aviation sector since of a combination of properties including high cycle fatigue high strength, and plasticity, high cycle fatigue maintainability, and outstanding fracture toughness [232]. $Ti_{10}V_2FAle$ has been effectively used in the landing gear systems of A-40-500/600, and Boeing 777 [233] due to its better ductility and lightweight ratio.

2. Improved mechanical properties at extremely high temperatures, as well as resistance against corrosion, are attained in boilers, both of which are necessary for optimal performance [234, 235]. Currently, HR3C steel is typically utilized for these purposes; however, $Al_{0.5}CoCrFeNi$ HEA, which can withstand supercritical temperatures, might be an effective replacement [236].

3. Material customization for maritime applications is still a substantial task that requires a comprehensive insight into tribological properties, anti-fouling characteristics, anti-corrosion potentials, & better mechanical behavior. Yuan et al [237] developed $AlCoCrNiFeCu_{0.5}$ HEAs, which have excellent antifouling
characteristics as well as resistance against corrosion & wear. Zhou et al [238] revealed that Al0.4CoCrNiFeCu is antibacterial.

4. HEAs are well explored for components of automobile industries due to their high strength, improved ductility, and toughness. HEAs enhance the load-bearing capacity and reduce the weight of components [239]. The reduction of weight without compromising safety leads to improvising fuel efficiency and reduces harmful gas emissions [240].

5. The remarkable properties of HEAs nitrides and carbides are similarly fascinating. Amorphous solid solution morphologies, as well as high mechanical strength and toughness, are possible. On instrument steels and high-speed steels, they could be used as coating materials and dissemination shields. High-entropy nitrides and carbides have also been shown to have enough potential to be used as biomedical coatings in recent investigations [150].
| S. No. | Applications                      | HEAs                                      | Key features                                                                                           | References       |
|-------|-----------------------------------|-------------------------------------------|--------------------------------------------------------------------------------------------------------|------------------|
| 1.    | Thermoelectric Materials          | Ni$_2$CrCuFeAl$_x$, Y$_1$CoCrFeNi, Al$_{0.5}$CrCoFeNi, PbFeSnSe | - Directly transform thermal energy into electric energy  
- Boost engine performance by harvesting exhaust heat                      | [202–204]       |
| 2.    | Electrode materials               | AlCoCrFeNi, FeNiCoMnCu, FeNiCoMnMg, Al$_{0.4}$FeCrNiCox | - Highly conductive, safe, and stable for high-performance energy storage devices.                   | [205–207]       |
| 3.    | Environmental safeguards          | AlFeCrNi, AlCrFeMnTi, AlFeCrMn,           | - Impurity elimination via adsorption  
- Minimal activation energy threshold  
- Greater reusability                                                      | [208, 209]      |
| 4.    | Energy storage                    | AlCrCoFeNi, FeNiCoMnMg, FeNiCoMgMn       | - Ultra-high-power density, quick energy propagation, and durability.                                 | [105, 117]       |
| 5.    | Gas monitoring and storage        | TiNbZrMoV, CoMnFeTiVZr, HfTiNbVZr, ZrVTiCrFeNi | - Ideal for storing hydrogen fuel  
- Improved safety, greater bulk density, and recyclability.                  | [210–213]       |
| 6.    | Radiation Shielding               | Al$_x$Cr$_x$Co$_x$Fe$_x$Ni, Cr$_x$Mn$_x$Ni$_x$Fe, Ti$_x$Hf$_x$Zr$_x$V$_x$Mo$_x$ | - Improved-strength and toughness  
- Sustain a harsh environment.                                              | [214–217]       |
| 7.    | Catalyst Materials                | Pt$_{20}$Fe$_{15}$Cu$_{10}$Ag$_{10}$Ni$_{11}$, Ni$_{20}$Fe$_{20}$Cr$_{15}$Mo$_{15}$Co$_{10}$, AlNiCuPdPtAu, AlNiCuPdPtCoAuFe | - Reducing energy usage, increase reaction rates.                                                 | [218, 219]       |
| 8.    | Magnetocaloric Materials          | Gd$_{25}$Y$_{20}$Al$_{30}$Nb$_{30}$M$_{25}$ (M = Co, Ni and Fe), FeCoNiMnCu, Mn$_{27}$Ge$_{25}$Si$_{4}$Cr$_{7}$Ni$_{33}$ | - Boost selectivity, and even alter the basic reaction.                                           | [220–222]       |
| 9.    | Electromagnetic Wave absorption   | AlFeCrCoNi, FeNiCoSi$_{10}$Al$_{0.6}$FeCoNiZnCu | - Affordable, extremely effective, and environmentally sustainable.                             | [223]            |
| 10.   | Superconducting materials         | Ta$_{14}$Nb$_{29}$Zr$_{12}$Ti$_{15}$Hf$_{15}$, Hf$_{15}$Ta$_{29}$Ni$_{15}$Ta$_{29}$Zr$_{15}$ | - Better energy efficient over standard refrigeration mode.                                        | [86, 223]       |
| 11.   | Shape memory alloy                | Ti$_{16.60}$Zr$_{16.60}$Hf$_{16.60}$Co$_{10}$Ni$_{15}$Cu$_{15}$, TiZrHfAlNb, Ti$_{16.60}$Zr$_{16.60}$Hf$_{16.60}$Ni$_{15}$Cu$_{15}$ | - Exceptional potential to capture microwaves and electromagnetic waves.                         | [224–226]       |
|       |                                   |                                           | - Superconductivity, Meissner effect, and efficient electron interaction                          |                  |
|       |                                   |                                           | - In regards to annealing temperature, crystallization temperature, and equilibrium temperature decreases. | [227, 228]       |
|       |                                   |                                           | - Advocated for high temperature applications                                                      |                  |
5. Challenges and the opportunities

It is noticeable out of this article that MA is widely employed in the tailoring of HEAs, although it still has certain shortcomings that must be overcome. As a result, this section adequately outlines the contemporary obstacles along with their conceivable ramifications. In addition, figure 17 schematically depicts the needs and challenges.

1. Despite the fact that HEAs have exceptional mechanical properties like increased strength at higher temperatures, better plasticity, enhanced hardness, and better toughness under very low temperature, they have still to find a practical application in which they would substitute well recognized conventional alloys such as nickel & Titanium alloys, and steel, that includes firmly anchored mechanical properties such as higher strength & stiffness, with suitable deformability, resistance against creep, still, they have to find a practical application. The majority of HEA research has mainly focused on their morphology and microstructure, as well as their mechanical and tribological properties. As a result, HEAs may be constrained to replicating the capabilities of their prior class of materials in the future.

2. HEA’s continued development should focus on improving mechanical and functional properties such as weldability, hydrogen embrittlement resistance, stress corrosion resistance, anti-fouling surface oxides layer, a combination of magnetic and invar response, piezoelectric energy utilizing capabilities, superconductivity, and anti-bacterial resistance, among others. As a result, HEAs must be developed to have improved mechanical and functional capabilities while maintaining a low overall cost.

3. In a significant advance, HEAs examined microstructure, mechanical and tribological properties. The emphasis should be transitioned toward the development of application-based HEAs. HEAs ought to develop explicitly for functional attributes that might lead to the development of new items and processes in response to forthcoming generation needs. It must be tailored to develop multifunctional elements with distinct characteristics that are challenging to achieve with a sole element. Our metallurgical academics, materials scientists, and engineers are still investigating HEAs with improved mechanical properties in order to achieve qualities such as wear-resistance to oxidation besides stress corrosion. These difficulties overlay the pathway for new materials to be designed and produced to suit future demands in aerospace, railways, maritime, power distribution equipment, transportation, and structural applications.

4. Because of their wide compositional range, nanocrystalline HEAs have a greater potential as catalysts. Nonetheless, the coherent and controlled development of these inherently intricate materials is a critical job associated with them [241]. The ability to quickly and effectively synthesize HEAs at elevated temperatures along with good thermal steadiness is now largely owing to developments in computational-assisted rational design [242, 243].
5. Weldability is an essential factor that cannot be neglected while using HEAs in any application; accordingly, special attention should be focused on knowing more about HEA weldability. Although work on CoCrFeNiMn HEA is promising, process parameters must be optimized in order to achieve an extremely effective joint having remarkable mechanical performance. The research shows that HEA may absorb impurities, yielding in unanticipated phases in non-equilibrium densification and high functional joint with superior mechanical characteristics. Impurities, on either hand, do not necessitate improved characteristics, thus microstructure homogenization is vital.

6. Grain refinement (via severe plastic deformation techniques and thermo-mechanical synthesis) and deformation attributes such as strain rate and temperature have a significant impact on mechanical properties. As a result, considerable attention should be dedicated to thermal stability, which governs the morphology and microstructure of HEAs, thereby improving their properties.

6. Concluding remarks

Mechanical alloying is a widely used method for synthesizing HEAs. This detailed evaluation explores the synthesis of HEAs using MA while considering its unique aspects. The primary goal of this research is to explore how to thoroughly assess phase development during HEA MA. Instead of a sophisticated, multiphase crystalline structure, several principal elements may form a single-phase crystalline structure, contrary to popular belief. Hardness, thermal stability, high-temperature strength, oxidation resistance, corrosion resistance, and wear endurance were all significantly improved when MA with fine HEAs powder disseminated evenly in the solid solution was used. Variations in MA times provide a wide range of crystalline forms and properties. As adequate alloying doesn’t occur when milling time is too short, and When the milling period is too long, since it is difficult to distinguish phases of powder particles, the milling duration should be decreased. The particle’s crystallite size reduces as milling time rises, yet lattice strain between the particles increases. It’s crucial to develop & synthesize HEAs with superior mechanical performances under a variety of environmental conditions, as well as phase stability and strengthening processes. According to the research, MA only forms crystalline phases with multiple phases and complex structures. Phases evolve into an intricate structure during consolidation and annealing, and numerous solid solution phases appear, signifying the advent of metastable phases. Since it provides high retention and densification, SPS is observed to be an extensively employed technique for HEA metal powder consolidation. Due to their hardness, HEAs have better wear resistance. Furthermore, HEA coatings have better corrosion resistance, according to various papers on corrosion behavior.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interest

No conflict of interest exists for this manuscript.

Funding

No Funding is available.

ORCID iDs

Akshay Kumar @ https://orcid.org/0000-0002-0491-2969

References

[1] Edelstein A, S, Murday J S and Rath B B 1997 Challenges in nanomaterials design Prog. Mater. Sci. 42 5–21
[2] Ding J, Xu H, Li X, Liu M and Zhang T 2021 The similarity of elements in multi-principle element alloys based on a new criterion for phase constitution Mater. Des. 207 109849
[3] Joseph J et al 2021 Computational design of thermally stable and precipitation-hardened Al-Co–Cr–Fe–Ni–Ti high entropy alloys J. Alloys Compd. 888 161496
[4] Wang X, Ma Y, Meng B and Wan M 2021 Effect of equal-channel angular pressing on microstructural evolution, mechanical property and biodegradability of an ultrafine-grained zinc alloy Mater. Sci. Eng. A 824 141857
[5] Kumar A and Parashar V 2016 Investigation of reinforcement content, load and sliding speed on the tribological behaviour of copper based silicon carbide composite using design of experiments Indian J. Sci. Technol. 9 1–5
[6] Singh A K, Soni S and Rana R S 2021 Surface structure evolution, mechanical behaviour, and fracture analysis of ultrasonic-assisted stir-squeeze cast high strength AA7068/ZrO 2p/Gr p composite under thermal aging Part. Sci. Technol. 39 1–20
[7] Hitam C N C, Aziz M A A, Ruhaimi A H and Taib M R 2021 Magnesium-based alloys for solid-state hydrogen storage applications: a review Int. J. Hydrogen Energy 47 31067–31083
[8] Bai H et al 2021 A review on wear-resistant coating with high hardness and high toughness on the surface of titanium alloy J. Alloys Compd. 882 166045
[9] Miracle D B and Senkov O N 2017 A critical review of high entropy alloys and related concepts Acta Mater. 122 448–511
[10] Zhang L S, Ma G L, Fu L C and Tian J Y 2013 Recent progress in high-entropy alloys Adv. Mater. Res. 631–632 227–32
[11] Tian Q, Zhang G, Yin K, Wang W, Cheng W and Wang Y 2019 The strengthening effects of relatively lightweight AlCoCrFeNi high entropy alloy Mater. Charact. 151 302–9
[12] Hemphill M A et al 2012 Fatigue behavior of Al0.3CoCrFeNi high entropy alloys Acta Mater. 60 5723–34
[13] Gwalandi B et al 2019 Compositionally graded high entropy alloy with a strong front and ductile back Mater. Today Commun. 20 100602
[14] Ferrari A and Körmann F 2020 Surface segregation in Cr–Mn–Fe–Co–Ni high entropy alloys Appl. Surf. Sci. 533 147471
[15] Wang Y, Yang Y, Yang H, Zhang M and Qiao J 2017 Effect of nitriding on the tribological properties of Al0.1Co0.7Cr0.2Fe0.1Ni high-entropy alloy J. Alloys Compd. 725 365–72
[16] Kumar G B V, Rao C S P, Selvaraj N and Bhagyashekar M S 2010 Studies on Al6061-SiC and Al7075-Al2O3 metal matrix composites J. Miner. Mater. Charact. Eng. 09 43–55
[17] Li K and Chen W 2021 Recent progress in high-entropy alloys for catalysts: synthesis, applications, and prospects Mater. Today Energy 20 100638
[18] He Q F, Ding Z Y, Ye F and Yang Y 2017 Design of high-entropy alloy: a perspective from nonideal mixing JOM 69 2092–8
[19] Manea C A et al 2019 HfNbTiBzr high entropy alloy processed by mechanical alloying UPB Sci. Bull. Ser. B Chem. Mater. Sci. 81 201–8
[20] Dang C, Surjadi J U, Gao I. and Lu Y 2018 Mechanical properties of nanostructured CoCrFeNiMn high-entropy alloy (HEA) coating, Front. Mater. 5 1–6
[21] Lu T W et al 2019 Microstructures and mechanical properties of CoCrFeNiAl0.3 high-entropy alloy thin films by pulsed laser deposition Appl. Surf. Sci. 494 72–9
[22] Tian L, Fu M and Xiong W 2018 Microstructural evolution of AlCoCrFeNiS high-entropy alloy powder during mechanical alloying and its coating performance Materials (Basel) 11 320
[23] Li N et al 2019 Progress in additive manufacturing on new materials: a review J. Mater. Sci. Technol. 35 242–69
[24] Yap C Y et al 2015 Review of selective laser melting: materials and applications Appl. Phys. Rev. 2 1041101
[25] Kuwahara K, Shiratori H, Fujieda T, Yamanaka K, Koizumi Y and Chiba A 2018 Mechanical and corrosion properties of AlCoCrFeNi high-entropy alloy fabricated with selective electron beam melting Addit. Manuf. 23 264–71
[26] Tong Y, Qi P, Liang X, Chen Y, Hu Y and Hu Z 2018 Different-shaped ultrafine MoNbTaW HEA powders prepared via mechanical alloying Mater. Rel (Basel) 10 1–8
[27] Sun C et al 2019 Microstructure and properties of CrMnFeCoNi high-entropy alloy prepared by mechanical alloying and spark plasma sintering J. Alloys Compd. 61 38–43
[28] Varalakshmi S, Appa Rao G, Kamara M and Murty B S 2010 Hot consolidation and mechanical properties of nanocrystalline equiatomic AIFeTiCrZnCu high entropy alloy after mechanical alloying J. Mater. Sci. 45 5138–43
[29] Veronesi P, Rosi R, Colombini E and Leonelli C 2015 Microwave-assisted preparation of high entropy alloys Technologies 3 318–97
[30] Yin S et al 2019 Deposition of FeCoNiCrMn high entropy alloy (HEA) coating via cold spraying J. Mater. Sci. Technol. 35 1003–7
Anupam A, Kumar S, Chavan N M, Murty B S and Kottada R S 2019 First report on cold-sprayed AlCoCrFeNi high-entropy alloy and its isothermal oxidation J. Mater. Res. 34 796–806

Popov V V, Katz-Demyanetz A, Koptyug A and Bamberger M 2019 Selective electron beam melting of Al53CoMoNbTa5 high entropy alloys using elemental powder blend Heliyon 5 e01188

Abbaszadeh S, Paksareh A, Omidvar H and Shafiei A 2020 Investigation of the high-temperature oxidation behavior of the Al65CoCrFeNi high entropy alloy Surfaces and Interfaces 21 100724

Zhou S et al 2019 High entropy alloy: a promising matrix for high-performance tungsten heavy alloys J. Alloys Compd. 777 1184–90

Li J et al 2019 Additive manufacturing of high-strength CrMnFeCoNi high-entropy alloys-bases composites with WC addition J. Mater. Sci. Technol. 35 2430–40

Li J, Gao J and Chen S H 2019 Effect of heat treatment on the phase evolution and mechanical properties of atomized AlCoCrFeNi high-entropy alloy powders J. Alloys Compd. 803 484–90

Shun T T and Du Y C 2009 Age hardening of the Al65CoCrFeNi5 high entropy alloy J. Alloys Compd. 478 269–72

Laurent-Brocq M et al 2015 Insights into the phase diagram of the CrMnFeCoNi high entropy alloy Acta Mater. 88 355–65

Li R, Mao J and Fan K 2011 Microstructure and mechanical properties of MgMnAlZnCu high entropy alloy cooling in three conditions Mater. Sci. Forum 686 235–41

Son S et al 2021 Superior anti-foiling properties of a CoCrFeMnNi high-entropy alloy Mater. Lett. 300 131030

Mueller-Grunt A, Alveen P, Rashed S, Uesldinger R and Moseley S 2019 The manufacture and characterization of WC-(Al) CoCrCuFeNi cemented carbides with nominally high entropy alloy binders Int. J. Refract. Met. Hard Mater. 84 105032

Qin G et al 2018 Effect of Co content on phase formation and mechanical properties of (Al)CoCrCuFeNi100-xCox high-entropy alloys Mater. Sci. Eng. A 710 200–5

He J Y et al 2014 Effects of Al addition on structural evolution and tensile properties of the FeCoNiCrMn high-entropy alloy system Acta Mater. 62 105–13

Gu Z, Mao P, Gou Y, Chao Y and Xi S 2020 Microstructure and properties of MgMoNbFeTi2Yx high entropy alloy coatings by laser cladding Surf. Coatings Technol. 402 126303

Ostovari A, Samodurova M N, Pashkeev K, Doubenskaia M, Sova A and Trofimov E A 2021 A novel intermediate temperature self-lubricating CoCrCu4FeNi high entropy alloy fabricated by direct laser cladding Tribol. Int. 156 106857

Zhang A, Han J, Su B, Li P and Meng J 2017 Microstructure, mechanical properties and tribological performance of CoCrFeNi high entropy alloy matrix self-lubricating composite Mater. Des. 114 253–63

Yang C, Li J, Chau H, Weng C, Chen C and Chou Y 2017 Preparation of high-entropy AlCoCrFeNiSi alloy powders by gas atomization process Mater. Chem. Phys. 202 151–8

Geng Y et al 2021 Nano-coupled heterostructure induced excellent magnetic and tribological properties in AlCoCrFeNi high entropy alloy Tribol. Int. 154 106662

Chandrakar B, Kumar A, Chandraker S, Rao K R and Chopkar M 2021 Microstructural and mechanical properties of AlCoCrFeNiSnX (x = 0 and 0.9) high entropy alloys Vacuum 184 109943

Wang T, Shukla S, Komarasamy M, Liu K and Mishra R S 2019 Towards heterogeneous AlCoCrFeNi high entropy alloy via friction stir processing Mater. Lett. 236 437–5

L. Rogal D, Kalita A, Tarasek P, Bobrowski and Czerwinski F 2017 Effect of SiC nano-particles on microstructure and mechanical properties of the CoCrFeMnNi high entropy alloy J. Alloys Compd. 708 344–52

Cheng H, Chen W, Liu X, Tang Q, Xie Y and Dai F 2018 Effect of Ti and C additions on the microstructure and mechanical properties of the FeCoCrNiMn high-entropy alloy Mater. Sci. Eng. A 719 192–8

Rao Z et al 2017 Microstructure, mechanical properties, and oxidation behavior of AlCr4.3Cu3Fe2MnNi high entropy alloys Adv. Eng. Mater. 19 1–10

Wei R, Sun H, Chen C, Tao J and Li F 2018 Formation of soft magnetic high entropy amorphous alloys composites containing in situ solid solution Magn. Mater. 449 63–7

Guirong L et al 2021 Effects of boron on microstructure and properties of microwave sintered FeCoNi33Cu22+ alloy high-entropy alloy J. Alloys Compd. 866 157848

Arab A, Guo Y, Zhou Q and Chen P 2019 Fabrication of nanocrystalline AlCoCrFeNi high entropy alloy through shock consolidation and mechanical alloying Entropy 21 480

Wang W, Wang W, Li, Wang S C, Tsai Y C, Lai C H and Yeh J W 2012 Effects of Al addition on the microstructure and mechanical properties of AlCoCrFeNi high-entropy alloys Intermetallics 26 44–51

Kuznetsov A V, Shaysultanov D G, Stepanov N D, Salishchev G A and Senkov O N 2012 Tensile properties of an AlCrCuNiFeCo high-entropy alloy in as-cast and wrought conditions Mater. Sci. Eng. A 533 107–18

Yeh J W et al 2004 Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes Adv. Eng. Mater. 6 299–303

Cantor B, Chang J T H, Knight P and Vincent A J B 2004 Microstructural development in equiatomic multicomponent alloys Mater. Sci. Eng. A 375–377 no. 1–2 SPEC. ISS. 33–8

Greer A L, Perpezelko H, Franks F, Cantor B and Cahn R W 2003 Grain refinement of alloys by inoculation of melts Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 361 479–95

Peter N I et al 2020 Early stage phase separation of AlCoCr27Fe25Ni high-entropy powder at the nanoscale J. Alloys Compd. 820 153149

Gudovatz B, George E P and Ritchie R O 2015 Processing, microstructure and mechanical properties of the CrMnFeCoNi high-entropy alloy JOM 67 2262–70

Tsai Y C and Yeh J W 2014 High-entropy alloys: a critical review Mater. Res. Lett. 2 107–23

Song Y, Kim D, Nam S, Lee K A and Choi H 2021 Effect of milling duration on oxide-formation behavior of oxide-dispersion-strengthened high-entropy alloys Arch. Metall. Mater. 66 735–40

Zhiming Li, Ludwig A et al 2018 Combinatorial metallurgical synthesis and processing of high-entropy alloys Journal of Materials Research 33 3156–31

George E P, Curtin W A and Tzan C C 2020 High entropy alloys: a focused review of mechanical properties and deformation mechanisms Acta Mater. 188 435–47

Pickering E J and Jones N G 2016 High-entropy alloys: a critical assessment of their founding principles and future prospects Int. Mater. Rev. 61 183–202

Yeh J W 2013 Alloy design strategies and future trends in high-entropy alloys JOM 65 1759–71

Gao M C, Liaw P K, Yeh J W and Zhang Y 2016 High-Entropy Alloys: Fundamentals and Applications.
Mater. Res. Express 9 (2022) 052001

[71] Praveen S and Kim H S 2018 High-entropy alloys: potential candidates for high-temperature applications—an overview Adv. Eng. Mater. 20 1–22
[72] Xu Q L, Zhang Y, Liu S H, Li C J and Li C X 2020 High-temperature oxidation behavior of CuAlNiCrFe high-entropy alloy bond coats deposited using high-speed laser cladding process Surf. Coatings Technol. 398 126093
[73] Lu T et al 2018 The influence of nanocrystalline CoNiFeAl0.5Co0.5Cu high-entropy alloy particles addition on microstructure and mechanical properties of SiCp/7075Al composites Mater. Sci. Eng. A 726 126–36
[74] Oh H S et al 2016 Lattice distortions in the FeCoNiCuMn high entropy alloy studied by theory and experiment Entropy 18 1–9
[75] Wang Z, Li J, Fang Q H, Liu B and Zhang L 2017 Investigation into nanoindenting mechanical response of AlCoCrFeNi high-entropy alloys using atomistic simulations Appl. Surf. Sci. 416 470–81
[76] Rangathan S 2003 Alloyed pleasures: multimetallic cocktails Curr. Sci. 85 1404–6
[77] Murty B S, Rangathan S, Yeh J W and Bhattacharjee P P 2019 High-Entropy Alloys.
[78] MacDonald B E et al 2017 Recent progress in high entropy alloy research JOM 69 2024–31
[79] Wei Q, Shen Q, Zhang J, Chen B, Luo G and Zhang L 2018 Microstructure and mechanical property of a novel ReMoTaW high-entropy alloy with high density Int. J. Fract. Met. Hard Mater. 77 8–11
[80] Varalakshmi S, Kamaraj M and Murty B S 2008 Synthesis and characterization of nanocrystalline AlFeTiCrZnCu high entropy solid solution by mechanical alloying J. Alloys Compd. 460 253–7
[81] Koc C C 2017 Nanocrystalline high-entropy alloys J. Mater. Res. 32 3435–44
[82] Sharma A S, Yadav S, Biswas K and Basu B 2018 High-entropy alloys and metallic nanocomposites: processing challenges, microstructure development and property enhancement Mater. Sci. Eng. R Reports 131 1–42
[83] Vaidya M, Muralikrishna G M and Bhat S B 2019 Mechanical alloying by high entropy alloys: a review J. Mater. Res. 34 664–86
[84] Gilman P S and Benjamin J S 1990 Mechanical alloying J. Japan Inst. Light Met. 40 850–5
[85] Suryanarayana C 2019 Mechanical alloying: a novel technique to synthesise advanced materials Research 2019 1–17
[86] Zhang B, Duan Y, Cui Y, Ma G, Wang T and Dong X 2018 A new mechanism for improving electromagnetic properties based on tunable crystallotextographic structures of FeCoNiMn x Al 0.4 high entropy alloy powders RSC Adv. 8 1436–4 14946
[87] Shivav V, Basu J, Shadangi Y, Singh M K and Mukhopadhyay N K 2018 Mechanico-chemical synthesis, thermal stability and phase evolution in AlCoCrFeNiMn high entropy alloy J. Alloys Compd. 757 87–97
[88] Lez S, Hrapkowics B, Karolus M and Golombek K 2021 Characteristics of the Mg–Zn–Ca–Ga alloy after mechanical alloying Materials 14 1226
[89] Amini M et al 2021 First-time synthesis of an unannealed Al23Cr16Ni14 decagonal quasicrystalline phase with the help of mechanical alloying and annealing procedures: a comparative study Powder Technol. 389 243–58
[90] He W et al 2021 Bimodal-grained high-strength nickel-base ODS alloy fabricated by mechanical alloying and hot extrusion Mater. Today Commun. 26 101921
[91] Ammar H R, Sivasankaran S and Alaboodi K A S 2021 Investigation of the microstructure and compressibility of biodegradable fe–mn–cu/w/co nanostructured alloy powders synthesized by mechanical alloying Materials (Basel) 14 3088
[92] Li Y, Chen C, Han T, Ranabhat I, Feng X and Shen Y 2017 Microstructures and oxidation behavior of NiCrAlCoY–Al composite coatings on Ti–6Al–4V alloy substrate via high-energy mechanical alloying method J. Alloys Compd. 697 268–81
[93] Shivam V, Shadangi Y, Basu J and Mukhopadhyay N K 2020 Evolution of phases, hardness and magnetic properties of AlCoCrFeNi high entropy alloy processed by mechanical alloying J. Alloys Compd. 832 154826
[94] Murali M et al 2018 Processing and characterisation of nano crystalline AlCoCrCuFeTi x high-entropy alloy Powder Metall. 60 1–10
[95] Lu T et al 2018 The influence of nanocrystalline CoNiFeAl0.4Ti0.6Cr0.5 high entropy alloy particles addition on microstructure and mechanical properties of SiCp / 7075Al composites Materials science & engineering A 726 126–36
[96] Praveen S, Murty B S and Kottada R S 2012 Alloying behavior in multi-component AlCoCrCuFeTi x high-entropy alloys Mater. Sci. Eng. A 534 83–9
[97] Moravcik I et al 2017 Microstructure and mechanical properties of Ni1.5Co1.5Fe2Ti0.5 high entropy alloy fabricated by mechanical alloying and spark plasma sintering Mater. Des. 119 141–50
[98] Mishra R K and Shahi R R 2017 Phase evolution and magnetic characteristics of TiFeNiCr and TiFeNiGM (M = Mn, Co) high entropy alloys J. Magn. Magn. Mater. 442 218–23
[99] Gómez-Esparza C D, Baledenero-López F, Gonzalez-Rodelas L, Baledenero-López J and Martín-Sánchez R 2016 Series of nanocrystalline high-entropy alloys produced by mechanical alloying Mater. Res. 19 39–46
[100] Raza A, Kang B, Lee J, Ryu H J and Hong S H 2018 PT CR Mater. Des. 141 11–19
[101] Ge W et al 2017 Characterization and applications of CuZrAlFeTiN high entropy alloy obtained by mechanical alloying and vacuum hot pressing sintering Adv. Powder Technol. 28 2556–63
[102] Oleszak D, Antolak-Dudka A and Kulik T 2018 High entropy multicomponent WMoNbZrV alloy processed by mechanical alloying Mater. Lett. 252 160–2
[103] Karthik G M, Panikar S, Ram G D J and Kottada R S 2017 Additive manufacturing of an aluminum matrix composite reinforced with nanocrystalline high-entropy alloy particles Mater. Sci. Eng. A 679 193–203
[104] Nam S, Kim M J, Hwang J Y and Choi H 2018 Strengthening of Al0.2CoCrFeCuNiTiX (x = 0, 1, 2) high-entropy alloys by grain refinement and using nanoscale carbides via powder metallurgical route J. Alloys Compd. 762 29–37
[105] Yadav S, Kumar A and Biswas K 2017 Wear behaviour of high entropy alloys containing soft dispersedoids (Ph, Bi) Mater. Chem. Phys. 182 153642
[106] Kang B, Lee J, Ryu H J and Hong S H 2018 Microstructure, mechanical property and Hall-Petch relationship of a light-weight refractory Al0.1CrNbVMo high entropy alloy fabricated by powder metallurgical process J. Alloys Compd. 767 1012–21
[107] Sun C, Li P, Xi S, Zhou Y, Li S and Yang X 2018 A new type of high entropy alloy composite Fe0.7Ni0.3Co0.25Cr0.5Mo0.5W0.5Nb,Co2 prepared by mechanical alloying and hot pressing sintering Mater. Sci. Eng. A 728 144–50
[108] Long Y, Su K, Zhang J, Liang X, Peng H and Li X 2017 Enhanced strength of a mechanical alloyed NbMoTaWVTi refractory high entropy alloy Materials (Basel) 11 1–8
[109] Joo S H et al 2017 Structure and properties of ultrafine-grained CoCrFeMnNi high-entropy alloys produced by mechanical alloying and spark plasma sintering J. Alloys Compd. 698 591–604
[110] Alijani F, Reihanian M and Gheisari K 2019 Study on phase formation in magnetic FeCoNiMnV high entropy alloy produced by mechanical alloying J. Alloys Compd. 773 623–30
[111] Yurkova A I, Chernyavsky V V, Bolbat V, Krüger M and Bogomol I 2019 Structure formation and mechanical properties of the high-entropy AlCuNiFeCr alloy prepared by mechanical alloying and spark plasma sintering J. Alloys Compd. 786 139–48
[112] Cheng H, Xie Y C, Tang Q H, Rao C and Dai P Q 2018 Microstructure and mechanical properties of FeCoCrNiMn high-entropy alloy produced by mechanical alloying and vacuum hot pressing sintering Trans. Nonferrous Met. Soc. China (English Ed.) 28 1360–7
[113] Ajay Kumar P and Perugu C S 2018 Synthesis of fcrcnbm high entropy alloy by mechanical alloying and study of their microstructure and mechanical properties Mater. Met. Mater. Ser. Part F1 669–75
[114] Wang G et al 2019 Synthesis and thermal stability of a nanocrystalline MoNbTaTi refractory high-entropy alloy via mechanical alloying Int. J. Refract. Met. Hard Mater. 84 104988
[115] Das S and Rohil P S 2018 Mechanical alloying of W–Mo–V–Cr–Ta high entropy alloys JOP Conf. Ser.: Mater. Sci. Eng. 346 012047
[116] Sun Y et al 2019 Phases, microstructures and mechanical properties of CoCrNiCuZn high-entropy alloy prepared by mechanical alloying and spark plasma sintering Entropy 21 122
[117] Kumar A, Swarnakar A K and Chopkar M 2018 Phase evolution and mechanical properties of AlCoCrFeNiSix high-entropy alloys synthesized by mechanical alloying and spark plasma sintering J. Mater. Eng. Perform. 27 3304–14
[118] Abbasi E and Dehghani K 2019 Phase prediction and microstructure of centrifugally cast non-equiatomic CoCrFeNi90Al1 high entropy alloys J. Alloys Compd. 783 292–9
[119] Zhang Y et al 2014 Microstructures and properties of high-entropy alloys Prog. Mater. Sci. 61 1–93
[120] Nayan N et al 2014 Hot deformation behaviour and microstructure control in AlCuFeNiFeCo high entropy alloy Intermetallics 55 145–53
[121] Tong C et al 2005 Mechanical performance of the AlScrCrCuFeNi high-entropy alloy system with multicomponent elements Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 36 1263–71
[122] Mohanty S et al 2017 Powder metallurgical processing of equiatomic AlCoCrFeNi high entropy alloy: microstructure and mechanical properties Mater. Sci. Eng. A 679 299–313
[123] Zakeri M, Ramezani M, Nazari A, Club Y R, Branch S and Branch S 2012 Effect of ball to powder weight ratio on the mechanochemical synthesis of MoSi2–TiC nanocomposite powder Materials Research 15 891–897
[124] Polanski M, Bystrzycki J, Kuziora P and Wyszyński M 2014 Why the ball to powder ratio effects of planetary balls J. Eur. Ceram. Soc. 34 821–9
[125] Lee W and Kwun S I 1996 The effects of process control agents on mechanical alloying mechanisms in the TiAl–Nb system Mater. Trans. A Phys. Metall. Mater. Sci. 37 53–57
[126] Fourmont A, Le Gallet S, Politano O, Desgranges C and Baras F 2020 Effects of planetary ball milling on AlCoCrFeNi high entropy alloys prepared by Spark Plasma Sintering: Experiments and molecular dynamics study Journal of Alloys and Compounds 820 153448
[127] Kumar S, Kumar D, Mauilık O, Pradhan A K, Kumar V and Patriaik A 2018 Synthesis and Air Jet Erosion Study of AlKFeNiMnNi0.5 (x = 0.3, 0.5) high-entropy alloys Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 49 5607–18
[128] Akhlaghi P, Amirian M and Parvin N 2021 The effect of processing parameters and heat-treatment on the microstructure and mechanical properties of FeCoCrFeNi high-entropy alloy Mater. Chem. Phys. Chem. Mater. 271 127272
[129] Cardoso K R, Izaias S and Vieira L D S 2020 Mechanical alloying and spark plasma sintering of AlCrCuFeZn high entropy alloy Materials Science and Technology 36 1861–1869
[130] Balandebro-Lopez F J, Herrera-Ramirez J M, Arredondo-Resa S P, Gómez-Esparza C D and Martínez-Sánchez R 2015 Simultaneous effect of mechanical alloying and arc-melting processes in the microstructure and hardness of an AlCoFeMoNiTi high-entropy alloy J. Alloys Compd. 643 5250–5
[131] Parakh A, Vaidya M, Kumar N, Chetty R and Mutry B S 2021 Effect of crystal structure and grain size on corrosion properties of AlCoCrFeNi high-entropy alloy J. Alloys Compd. 863 158056
[132] Fourmont A, Le Gallet S, Politano O, Desgranges C and Baras F 2020 Effects of planetary ball milling on AlCoCrFeNi high entropy alloys prepared by Spark Plasma Sintering: experiments and molecular dynamics study Journal of Alloys and Compounds 820 153448
[133] Fourmont A et al 2020 Effects of planetary ball milling on AlCoCrFeNi high entropy alloys prepared by Spark Plasma Sintering: experiments and molecular dynamics study Journal of Alloys and Compounds 820 153448
[134] Geng Y et al 2020 Microstructure, mechanical and vacuum high-temperature tribological properties of AlCoCrFeNi high-entropy alloy based solid-lubricating composites Tribol. Int. 151 106444
[135] Duan Y, Wen X, Zhang B, Ma G and Wang T 2020 Optimizing the electromagnetic properties of the FeCoNiAlCrx high entropy alloy powders by composition adjustment and annealing treatment J. Magn. Magn. Mater. 497 165947
[136] Suryanarayana C 2001 Mechanical alloying and milling Prog. Mater. Sci. 46 1–184
[137] Shaw L, Zawrah M, Villegas J, Luo H and Miracle D 2003 Effects of process-control agents on mechanical alloying of nanostructured aluminum alloys Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 34 159–70
[138] Ruiz-Esparza-Rodríguez M A et al 2021 Effect of process control agent and Al concentration on synthesis and phase stability of a mechanically alloyed AlScrCrCuFeNi Mn high-entropy alloy J. Alloys Compd. 882 141
[139] Lee W and Kwun S I 1996 The effects of process control agents in mechanical alloying mechanisms in the Ti–Al system J. Alloys Compd. 216 193–9
[140] Lu L and Zhang Y F 1999 Influence of process control agent on interdiffusion between Al and Mg during mechanical alloying Journal of alloys and compounds 290 279–83
[141] Ju R, Su J B, Berlanga R, Bonastre J and Escoda L 2007 The effects of process control agents on mechanical alloying behavior of a Fe–Zr based alloy Journal of alloys and compounds 315 472–6
[142] Yadav S, Kumar A and Biswas K 2018 Wear behaviour of high entropy alloys containing soft dispersoids (Pb, Bi) Mater. Chem. Phys. 210 222–32
[143] Jin G et al 2018 Applied surface science high temperature wear performance of laser-cladded FeCoNiAlCu high-entropy alloy coating Appl. Surf. Sci. 445 113–22
[144] Li B, Qian B, Xu Y, Liu Z and Xuan F 2019 Fine-structured CoCrFeNiMn high-entropy alloy matrix composite with 12 wt% TiN particle reinforcements via selective laser melting assisted additive manufacturing Materials Letters 252 88–91
[145] Zhang M et al 2018 Effect of Binding and Dispersion Behavior of High-Entropy Alloy (HEA) Powders on the Microstructure and Mechanical Properties in a Novel HEA/Diamond Composite Entropy 20 924
[146] Qiao Y et al 2020 Preparation of TiZrNbTa refractory high-entropy alloy powder by mechanical alloying with liquid process control agents Intermetallics 126 106900
[147] Zhang Y et al 2018 Synthesis of fcrcnbm high entropy alloy by mechanical alloying and study of their microstructure and mechanical properties Mater. Met. Mater. Ser. Part F1 669–75
Figiel H, Zoga K, Kumar S, Rani P, Patnaik A, Pradhan A.K. and Kumar V 2019 Effect of cobalt content on wear behaviour of Al0.4FeCrNiCox

Zhuang Y X, Zhang X L and Gu X Y 2018 Effect of molybdenum on phases, microstructure and mechanical properties of Al0.25, 0.5, 1.0 mol

Wang Y P, Li B S, Ren M X, Yang C and Fu H Z 2008 Microstructure and compressive properties of AlCrFeCoNi high entropy alloy

Pan J, Dai T, Lu T, Ni X, Dai J and Li M 2018 Microstructure and mechanical properties of Nb25Mo25Ta25W25 and

Ji W Fu Z Liu B Fan Q C, Li B S and Zhang Y 2014 The microstructure and properties of

Cheng H, Liu X, Tang Q, Wang W, Yan X and Dai P 2019 Microstructure and mechanical properties of FeCoCrNiMnAlx high-entropy alloy composite formed by laser cladding

entropy alloys prepared by mechanical alloying and hot-pressed sintering

Co25Ni25Fe25Al7.5Cu17.5 high-entropy alloy

Scr. Mater.

2018 Synergic strengthening by oxide and coherent precipitate dispersions in high-entropy alloy prepared by powder metallurgical process Mater. Sci. Eng. A 712 616–24

Moravcik et al 2018 Synergic strengthening by oxide and coherent precipitate dispersions in high-entropy alloy prepared by powder metallurgy Scr. Mater. 157 24–9

Fu Z et al 2016 Microstructure and strengthening mechanisms in an FCC structured single-phase nanocrystalline

Co0.33Ni0.33Fe0.33Al0.33Cu0.33 high-entropy alloy Acta Mater. 107 59–71

Ji We et al 2014 Mechanical alloying synthesis and spark plasma sintering consolidation of CoCrFeNiAl high-entropy alloy J. Alloys Compd. 589 61–6

Chen W, Fu Z, Fang S, Xiao H and Zhu D 2013 Alloying behavior, microstructure and mechanical properties in a FeNiCrCoAlx high entropy alloy Mater. Des. 51 851–60

Fan QC, Li BS and Zhang Y 2014 The microstructure and properties of (FeCrNiCo)AlxCu1–x high-entropy alloys and their TiC-reinforced composites Mater. Sci. Eng. A 598 244–50

Liu Y, Wang J, Fang Q, Liu B, Wu Y and Chen S 2016 Intermetallics Preparation of super of FeCoCrNi high entropy alloy by spark plasma sintering gas atomized powder Intermetallics 68 16–22

Liu B et al 2016 Intermetallics microstructure and mechanical properties of equiatomic FeCoCrNi high-entropy alloy prepared via powder extrusion Intermetallics 25 25–30

Tsai C, Tsai M, Yeh J and Yang C 2010 Effect of temperature on mechanical properties of Al0.33CoCrCuFeNi wrought alloy 490 160–5

Ko YJ and Hong S 2018 Microstructural evolution and mechanical performance of carbon-containing CoCrFeMnNi-C high entropy alloys J. Alloys Compd. 743 115–25

WangYP, LiBS, RenMX, YangC and FuHZ 2008 Microstructure and compressive properties of AlFeCrCoNi high entropy alloy Mater. Sci. Eng. A 491 154–8

Zhuang YX, ZhangXL and GuXY 2018 Effect of molybdenum on phases, microstructure and mechanical properties of Al0.5 CoFeMo x Ni high entropy alloys 743 514–22

Chen W et al 2019 Effect of ball milling on microstructure and mechanical properties of 6061Al matrix composites reinforced with high-entropy alloy particles Mater. Sci. Eng. A 762 138116

Yao HW, Qiao JW, HawkJA, ZhouHF, ChenMW and GaoMC 2017 Mechanical properties of refractory high-entropy alloys: experiments and modeling J. Alloys Compd. 696 1139–50

ChengH, LiuX, TangQ, WangW, YanX and DaiP 2019 Microstructure and mechanical properties of FeCoCrNiMnAlx high-entropy alloys prepared by mechanical alloying and hot-pressed sintering J. Alloys Compd. 775 742–51

HouJ, ZhangM, MaS, LiwPK, ZhangY and QiaoJ 2017 Materials science & engineering a strengthening in Al25CoCrFeNi high-entropy alloys by cold rolling Mater. Sci. Eng. A 707 593–607

Alcalá M.D. et al. 2018 Effects of milling time, sintering temperature, Al content on the chemical nature, microhardness and microstructure of mechanochemically synthesized FeCoCrNiCoMn high entropy alloy Journal of Alloys and Compounds 749 834–843

Pan J, DaiT, LuT, NiX, DaiJ and LiM 2018 Microstructural and mechanical properties of Nb25M025Ta25W25 and Ti56Nb15Mo25Ta25W25 high-entropy alloys prepared by mechanical alloying and spark plasma sintering Mater. Sci. Eng. A 738 362–6

JuanC et al 2015 Intermetallics Enhanced mechanical properties of HfMo0.2Ta0.2Zr0.6 high-entropy alloys Intermetallics 62 76–83

Geng Y et al 2020 Sliding wear-induced chemical nanolayering in Cu–Ag, and its implications for high wear resistance Tribol. Int. 151 106444

YadavS, SarkarS, AggarwalA, KumarA and BiswasK 2018 Wear and mechanical properties of novel (CuFeTeZn)n100-xPbx high entropy alloy composite via mechanical alloying and spark plasma sintering Wear 410–411 93–109

Nagarjuna C et al 2021 Applied Surface Science Worn surface and subsurface layer structure formation behavior on wear mechanism of CoCrFeMnNi high-entropy alloy in different sliding conditions Appl. Surf. Sci. 549 109203

KumarS, PattnaikA, KumarA and Vinod P 2019 Dry sliding wear of Al0.4FeCrNiCo(x = 0, 0.25, 0.5, 1.0 mol) high-entropy alloys saurav Metalloge. Microstruct. Anal. 8 545–57

DollmannA, KaufmannA, HeilmaierM, HaugC and GreinerC 2020 Microstructural changes in CoCrFeMnNi under mild tribological load J. Mater. Sci. 55 12335–72

JiangPF, ZhangCH, ZhangS, ZhangJB, ChenJ and LiuY 2020 Fabrication and wear behavior of TiC-reinforced FeCoCrAlCu-based high entropy alloy coatings by laser surface alloying Mater. Chem. Phys. 253 125571

Gao X et al. 2020 A comparison of the dry sliding wear of single-phase F.C.C. carbon-doped Fe0.4Ni11.3Mn34.8Al7.5Cr6 and CoCrFeMnNi high-entropy alloys with 316 stainless steel Mater. Charact. 170 110693

Cai Y et al 2021 Fracture and wear mechanisms of FeMnCrNiCo + x(TiC) composite high-entropy alloy cladding layers Applied surface science 543 148794

VermaA, TarateP, AbhyankarAC, MohapeMR and GowtamDS 2019 High temperature wear in CoCrFeNiCu high entropy alloys: the role of Cu Scr. Mater. 161 28–31

KumarS, PattnaikA, PradhanAK and KumarV 2019 Room temperature wear study of Al0.4FeCrNiCo(x = 0, 0.25, 0.5, 1.0 mol) high-entropy alloys under oil lubricating conditions J. Mater. Res. 34 841–53

KumarS, RanJ, PattnaikA, PradhanAK and KumarV 2019 Effect of cobalt content on wear behaviour of Al0.4FeCrNiCo(x = 0, 0.25, 0.5, 1.0 mol) high-entropy alloys tested under demineralised water with and without 3.5% NaCl solution Mater. Res. Express 6 086533

Shang C, AxinteE, GeW, ZhangZ and WangY 2017 High-entropy alloy coatings with excellent mechanical, corrosion resistance and magnetic properties prepared by mechanical alloying and hot pressing sintering Surfaces and Interfaces 9 36–43

GuZ, XiS, MaoP and WangCW 2020 Microstructure and wear behavior of mechanically alloyed powder Al0.6Fe0.4Nb17Fe23Mn25 high entropy alloy coating formed by laser cladding Surf. Coatings Technol. 401 126244

Fiegél H, Zogal O and YartysV 2005 Effect of iron content on the microstructure evolution, mechanical properties and wear resistance of FeCoCrNi high-entropy alloy system produced via MA-SPS Parisa J. Alloys Compd. 404–406.
[186] Shang C, Axinte E, Ge W, Zhang Z and Wang Y 2017 CoCrFeNi(W1 – xMox) high-entropy alloy coatings with excellent mechanical properties and corrosion resistance prepared by mechanical alloying and hot press sintering Surfaces and Interfaces 9 36–43
[187] Mozanna P, Toroghinejad M R, Zargar T and Cavaliere P 2022 Investigation of hardness, wear and magnetic properties of NiCoCrFeZr HEA prepared through mechanical alloying and spark plasma sintering J. Alloys Compd. 892 161924
[188] Ravi R and Bakhshi SR 2021 Microstructural evolution and wear behavior of carbon added CoCrFeMnNi multi-component alloy fabricated by mechanical alloying and spark plasma sintering J. Alloys Compd. 883 160879
[189] Xu J, Wang S, Shang C, Huang S and Wang Y 2019 Microstructure and properties of CoCrFeNi(WC) high-entropy alloy coatings prepared using mechanical alloying and hot press sintering Coatings 9 16
[190] Deng G et al 2020 Effects of normal load and velocity on the dry sliding tribological behaviour of CoCrFeNiMo0.5 high entropy alloy Tribol. Int. 144 106166
[191] Huang Y, Wang Z, Xu Z, Zang X and Chen X 2021 Microstructure and properties of TiNbZrMo high entropy alloy coating Mater. Lett. 285 3–6
[192] Yang Q, Tang Y, Wen Y, Zhang Q, Deng D and Nai X 2018 Microstructures and properties of CoCrFeNiMox high-entropy alloys fabricated by mechanical alloying and spark plasma sintering Powder. Metall. 611 15–22
[193] Liang M L et al 2022 Microstructure and sliding wear behavior of FeCoNiCr0.8Al0.2 high-entropy alloy for different durations Int. J. Refract. Met. Hart. Mater. 103 105767
[194] Pole M, Sadeghuladijani M, Shitiri J, Ayyagari A and Mukherjee S 2020 High temperature wear behavior of refractory high entropy alloys based on 4–5–6 elemental palette Journal of alloys and compounds 843 156004
[195] Malati N, Popoola A P I, Lengpeng T and Pityana S 2020 tribological and corrosion properties of laser additive manufactured AlCrFeNiCu high entropy alloy Materials today proceedings 28 944–8
[196] Shi Y, Yang B and Liaw P K 2017 Corrosion-resistant high-entropy alloys: a review 1–18
[197] Nascimento C B, Donato U, Rios C T, De Oliveira M C L and Antunes R A 2022 A review on corrosion of high entropy alloys: exploring the interplay between corrosion properties, alloy composition, passive film stability and materials selection Mater. Res. 25 e20210442
[198] Shi Y, Yang B, Xie X, Brechtl J, Dahmen K A and Liaw P K 2017 Corrosion of Al x CoCrFeNi high-entropy alloys: Al-content and potential scan–rate dependent pitting behavior Eval. Program Plann. 119 33–45
[199] Fu Y, Li L, Luo H, Du C and Li X 2021 Recent advances on environmental corrosion behavior and mechanism of high-entropy alloys Journal of Materials Science and Technology 80 217–33
[200] Chai W, Lu T and Pan Y 2020 role of Cr–induced segregation Intermetallics alloys 116 1–10
[201] Shi Y et al 2018 Homogenization of AlCoCrFeNi high-entropy alloys with improved corrosion resistance Corros. Sci. 133 120–31
[202] Crane D T and Lagranjande J W 2010 Progress report on BSST-Led US department of energy automotive waste heat recovery program Journal of electronics materials 39 2142–2142
[203] Kush L et al 2020 Thermoelectric behaviour with high lattice thermal conductivity of Nickel base Ni2CuCrFeAlx (x = 0.5, 1.0, 1.5 and 2.5) high entropy alloys Materials Research Expression 7 1–16
[204] Dong W, Zhou Z, Zhang L, Zhang M and Gong Li R L 2018 Effects of Y, GdCu, and Al addition on the thermoelectric behavior of CoCrFeNi high entropy alloys sintering Metals (Basel) 8 781
[205] Kong K, Hyun J, Kim Y, Kim W and Kim D 2019 Nanoporous structure synthesized by selective phase dissolution of AlCoCrFeNi high entropy alloy and its electrochemical properties as supercapacitor electrode J. Power Sources 437 226927
[206] Xu X et al 2020 High-entropy alloy nanoparticles on aligned electrosprun carbon nano fi bers for supercapacitors J. Alloys Compd. 822 153642
[207] Kumar S, Patnaik A, Pradhan A K and Kumar V 2019 Effect of cobalt content on thermal, mechanical, and microstructural properties of AlxFeCrNiCox (x = 0.25, 0.5, 1.0 and 2.5) high entropy alloys Mater. Research Express 6 45213
[208] Wu S, Gao W, Lu T and Pan Y 2020 Co-free high-entropy alloy powders immobilized by electrospray and microfluidics for decolorization of Azo dye solutions Scientific reports 6 45213
[209] Kunc I, Polanski M and Bystrzycki J 2013 Structure and hydrogen storage properties of a high entropy ZrTiVCrFeNi alloy synthesized using Laser Engineered Net Shaping Intermetallics 9046 –
[210] Kunc I, Polanski M and Bystrzycki J 2013 Structure and hydrogen storage properties of a high entropy ZrTiVCrFeNi alloy synthesized using Laser Engineered Net Shaping (LENS) Int. J. Hydrogen Energy 38 12180–9
[211] Ullner U et al 2014 Effect of oxygen on the microstructure and hydrogen storage properties of Ti–Fe–Cr–Fe quaternary solid solutions International journal of Hydrogen Energy 39 20000–20008
[212] Kao Y et al 2010 Hydrogen storage properties of multi-principal-component CoFeMnTi x V y Zr x alloys Int. J. Hydrogen Energy 35 9046–59
[213] Kunc I, Polanski M and Bystrzycki J 2014 ScienceDirect microstructure and hydrogen storage properties of a TiZrNbMoV high entropy alloy synthesized using laser engineered net shaping (LENS) Int. J. Hydrogen Energy 39 9904–10
[214] Xia S, Yang X, Yang T F, Liu S and Zhang Z 2015 Irradiation resistance in Al x CoCrFeNi high entropy alloys JOM 67 2340–4
[215] Egami T, Guo W, Rack P D and Nagase T 2014 Irradiation resistance of multicomponent alloys Metallurgical and materials transactions A 45 180–183
[216] Yang L, Ge H, Zhang J, Xiong T, Jin Q and Zhou Y 2019 Journal of materials science & technology high He–ion irradiation resistance of CrMnFeCoNi high-entropy alloy revealed by comparison study with Ni and Si0.5Fe3 J. Mater. Sci. Technol. 35 300–5
[217] ZhrhV Y et al 2019 Journal of materials science & technology a promising new class of irradiation tolerant materials J. Mater. Sci. Technol. 35 369–73
[218] Zhang G, Ming K, Kang J, Huang Q and Zhang Z 2018 Electrochemica Acta High entropy alloy as a highly active and stable electrocatalyst for hydrogen evolution reaction Electrochim. Acta 279 19–23
[219] Charman W. N. et al 1972 A search for pulses of fluorescence produced by supernovae in the upper atmosphere Journal of Physics A: General Physics 5 773
[220] Bruck E, Tegus O, Zhang L, Li X W, De Boer F R and Buschow K H J 2004 Magnetic refrigeration near room temperature with Fe 2 P-based compounds Journal of alloys and compounds 383 32–6
[221] Huo J, Luo L, Men H, Wang X and Inoue A 2015 the magnetocaloric effect of Gd–Th–Dy–Al–M (M = Fe, Co and Ni) high-entropy bulk metallic glasses Intermetallics 58 31–5
[222] Sarlar K, Tekg A and Kucuk I 2019 Electromagnetics magnetocaloric properties of rare-earth–free Mn 27 Cr 7 Ni 33 Ge 25 Si 8 high-entropy alloy IEEE Magnetic Letters 10 8–12
[223] Yang P, Liu Y, Zhao X, Cheng J and Li H 2016 Electromagnetic wave absorption properties of mechanically alloyed FeCoNiCrAl high entropy alloy powders Adv. Powder Technol. 27 1128–33
Koželj P et al 2014 Discovery of a superconducting high-entropy alloy Physical Review Letters 113 107001
Jasiewicz K, Wiendlocha B, Korbe P, Kaprzyk S and Tobola J 2016 Superconductivity of $T_x$$_{34}$Nb$_y$Hf$ _{14}$Zr$_{14}$Ti$_{14}$ high entropy alloy from first principles calculations Rapid Research Letters 10 415–419
Ishizu N and Kitagawa J 2016 Results in physics new high-entropy alloy superconductor Hf$_{34}$Nb$_{33}$Ti$_{14}$V$_{13}$Zr$_{14}$ Results Phys. 13 102275
Firstov G S, Kosorukova T A, Koval Y N and Odnosum V V 2015 High entropy shape memory alloys Mater. Today Proc. 2 S499–503
Kosorukova G S, F T A and Koval Y N 2015 Directions for high-temperature shape memory alloys’ improvement: straight way to high-entropy materials! Shape Mem. Superalductivity 1 400–7
Kumar D V Ravi, Seenappa, Ravi Kumar V and Prakash Rao C R 2018 Influence of T6-heat treatment on mechanical properties of Al7075 alloy reinforced with Cenosphere Mater. Today Proc. 5 25036–44
Elmer T, Worall M, Wu S and Riffat S 2016 An experimental study of a novel integrated desiccant air conditioning system for building applications Energy Build. 111 434–45
Shi Q, Tse Y Y and Higginson R L 2020 Microstructure Evolution and Microhardness Analysis of Metastable Beta Titanium Alloy Ti-15V-3Cr-3Al-3Sn Consolidated Using Equal-Channel Angular Pressing from Machining Chips journal of Materials Engineering and Performance 29 4142–4153
Dai J, Zhu J, Chen C and Weng F 2016 High temperature oxidation behavior and research status of modifications on improving high temperature oxidation resistance of titanium alloys and titanium aluminides: a review J. Alloys Compd. 685 784–98
Quan G, Lu W, Liang J and Pu S 2015 Evaluation of the hot workability corresponding to complex deformation mechanism evolution for Ti-10V-2Fe-3Al alloy in a wide condition range J. Mater. Process. Tech. 221 66–79
Senkov O N, Senkova S V, Dimiduk D M, Woodward C and Miracle D B 2012 Oxidation behavior of a refractory NbCrMo 0.5 Ta 0.5 TiZr alloy Journal of Materials Science 47 6522–6534
Liu C M, Wang H M, Zhang S Q, Tang H B and Zhang A L 2014 Microstructure and oxidation behavior of new refractory high entropy alloys J. Alloys Compd. 583 162–9
Liu Y, Cheng C, Shang J, Wang R, Li P and Zhao J 2015 Oxidation behavior of high-entropy alloys AlxCoCrFeNi (x = 0.15, 0.4) in supercritical water and comparison with HR3C steel Trans. Nonferrous Met. Soc. China 25 1341–51
Yu Y, Xu N, Zhu S, Qiao Z and Zhang J 2021 Journal of Materials Science & Technology A novel Cu-doped high entropy alloy with excellent comprehensive performances for marine application J. Mater. Sci. Technol. 69 48–59
Zhou E et al 2020 A novel Cu-bearing high-entropy alloy with significant antibacterial behavior against corrosive marine biofilms J. Mater. Sci. Technol. 46 201–10
Maulik O, Kumar D, Kumar S, Devagan S K and Kumar V 2018 Structure and properties of lightweight high entropy alloys: a brief review Mater. Res. Express 5 052001
Sathiyamoorthi P and Kim H S 2022 Progress in materials science high-entropy alloys with heterogeneous microstructure: processing and mechanical properties Prog. Mater Sci. 123 100709
Xie P et al 2019 Highly efficient decomposition of ammonia using high-entropy alloy catalysts Nat. Commun. 10 1–12
Yao Y et al 2020 Computationally aided, entropy-driven synthesis of highly efficient and durable multi-elemental alloy catalysts Sci. Adv. 6 1–12
Li T et al 2021 Denary oxide nanoparticles as highly stable catalysts for methane combustion Nat. Catal. 4 439