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Aluminium matrix composites reinforced with high entropy alloys: A comprehensive review on interfacial reactions, mechanical, corrosion, and tribological characteristics

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ABSTRACT

Aluminium matrix composites (AMCs) reinforced with high entropy alloy particulates (HEAp) represent an innovative category of metal-matrix composites with considerable potential for fulfilling the stringent demands of emerging technological applications. Their appeal lies in the advantageous combination of toughness, strength, ductility, and enhanced workability, addressing acknowledged limitations associated with ceramic-reinforced AMCs. The heightened performance of these composites is attributed to improved wettability between the aluminium matrix and HEAp reinforcement, alongside the intrinsic ductility and hardness of HEAp. This review explores the suitability of high entropy alloys as substitutes for ceramic materials in reinforcing aluminium matrix composites. The mechanical, corrosion, thermal and wear properties of AMCs reinforced with HEAp are thoroughly examined, encompassing fabrication characteristics and interfacial reactions. The incorporation of HEAp is found to notably enhance the strength-ductility ratio of AMCs. Remarkably, HEAp bring about significant improvements in the wear and corrosion resistance of AMCs. The report accentuates the performance benefits and certain challenges associated with the application of HEAp reinforcement in AMCs. Ultimately, this review proposes potential avenues for future research in this domain, outlining directions for further exploration and development.

1. Introduction

Researchers are on the quest for lightweight materials with high strength, strong corrosion resistance, great creep resistance, and superior abrasion resistance [1]. One interesting option that has been explored to satisfy these service requirements is aluminium matrix composites (AMCs) [2]. This is due to their remarkable characteristics, which include low processing costs, low density, and a good combination of mechanical properties [3]. The favourable characteristics of these AMCs render them appealing for use in the transportation industries, automotive, aircraft, marine, military, structural and construction systems, biomedical, sports and leisure equipment [4]. Traditionally, ceramic materials in the form of particulates, whiskers or fibres are used to reinforce AMCs, and the most commonly used particulates include alumina, silicon carbide, boron carbide, titania, diamond, and graphite particulates [2,5]. Some considerable improvements in terms of their mechanical strength have been reported owing to these ceramic reinforcements in the aluminium matrix. However, there are significant drawbacks associated with these ceramic reinforcements [6].

Reinforcing particulate segregation or agglomeration, intrinsic

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brittleness, interfacial reaction, and poor wetting characteristics between the ceramic reinforcement and the aluminium matrix are some of the limitations which result in poor interfacial bonding, degradation, poor ductility and low fracture toughness, poor workability, and poor thermal fatigue properties [7,8]. These constraints become problematic when designing components for structural and stress-bearing applications [9]. Ceramic reinforcements in aluminium matrix have been reported to raise some environmental concerns due to their attendant challenges with recycling [10]. To address these problems in AMCs, some researchers have looked into the possibility of altering the composition and geometry of the reinforcing material [7,11]. The idea of using hybrid reinforcements and nano-sized reinforcing particles to address the problem of poor ductility in AMCs have been widely reported by a number of authors [12–15]. Although there has been considerable progress with these methods, but the improvement realised is not acceptable especially in applications where ductility and toughness is a major concern [16].

Recent materials design initiatives have aimed at employing metallic systems as a substitute for ceramic reinforcements, and the idea is based on the encouraging outcomes of laboratory research [6]. Improved wettability between the matrix and the metallic reinforcement, as well as good bonding at the metal/reinforcement interface, are two benefits of using metallic systems as reinforcements in the fabrication of AMCs. Consequently, the ductility and toughness are improved due to metallic reinforcements' innate ductility and continuous interfacial bonding as a result of the enhanced wetability between the matrix and the metallic reinforcement [15].

High entropy alloys (HEAs) are a relatively new class of metallic systems consisting of four or more metallic constituents in almost equiatomic ratios [17,18]. The high-entropy alloy contains a significant number of main elements with minimal differences in molar content. This results in an increased mixing entropy, leading to the formation of simple solid solutions with structures such as body-centered cubic (BCC), face-centered cubic (FCC), and hexagonal close packing (HCP) [19]. Their peculiar constitution results in certain unique characteristics, which include the lattice distortion effect; slow diffusion effect; high entropy effect; and the cocktail effect [19–21]. HEAs have a number of interesting properties including a good combination of mechanical strength and ductility, extraordinary wear resistance, outstanding corrosion resistance, excellent oxidation resistance, and exceptional thermal stability [17,19]. HEAs show higher ductility when compared to ceramics and amorphous alloys, and as such, they tend to perform better when used as reinforcement in AMCs [6,20,22]. AMCs reinforced with hard and brittle ceramics particle often exhibit circumstances that promote rapid crack propagation. The intrinsic toughness and ductility of HEA particles, in comparison to ceramic systems and amorphous alloys (metallic glasses), contribute to enhanced resistance against crack propagation [23–26]. Their enhanced ability to yield and deform allows for the blunting of crack tips, therefore reducing the potential for increased stress levels at the crack's tip near the interfaces between the matrix and the reinforcement [23–26]. Unlike ceramics, which have an intrinsic brittleness, stress conditions that promote rapid crack propagation and brittle fracture can be caused by particle cracking, pull-out, interface cracking, or particle decohesion [23,24]. Also, ceramic materials have been observed to include atoms held together by chemical bonds, the most common of which are covalent and ionic bonds. Metals, on the other hand, are distinguished by the presence of metallic bonding. The utilization of different materials with different chemical bonds leads to poor wettability. Therefore, the utilization of reinforcements with metallic bonding in AMCs will effectively addresses the issue of wettability in AMCs and leads to improved adhesion at the interface between the matrix and reinforcement in a metal-metal system, as opposed to a metal-ceramic system [24–26].

The main objective of this review is to evaluate the influence of processing methods, interfacial reactions and reinforcement proportion on the strength-ductility ratio and functional properties of AMCs reinforced with HEAs with respect to the properties of their counterparts reinforced with ceramic materials. Although there are some review works on the AMCs reinforced with ceramic particles [23,24], agrowaste derivatives [5], metallic glass [25], shape memory alloys [26]; only very few authors including [6] have reported the use of HEA particles as reinforcement in AMCs, and none of those reviews have systematically and comprehensively established the role of the matrix/reinforcement interface interactions on their performance evaluation, as well as their corrosion and wear properties in relation to the HEAs reinforcement.

1.1. *Method for selecting publications considered in this review*

A comprehensive analysis of the available literature was undertaken to investigate the interfacial reactions, mechanical, corrosion and tribological properties of aluminium matrix composites reinforced with HEA. The Scopus database was chosen after conducting an initial search in other databases. Due to its extensive usage and significant effectiveness, this database demonstrates a higher volume of published articles related to the subject matter in comparison to other databases. A comprehensive search was performed on the Scopus database with the specified keywords, identifying several scholarly articles, monographs, and conference papers deemed pertinent to the research. The following keywords were utilized: "aluminium matrix composite*" AND "high entropy alloys*" OR "multicomponent alloys*" AND "aluminium matrix composite*" OR "multi-principal element alloys*" AND "aluminium based composite*" OR "complex concentration alloys*" AND "aluminium matrix compoite*" OR "aluminium based composite*" AND "multi principal component alloy*". After using the designated keywords in the title, abstract, and keyword fields, a total of 132 articles were found. In this study, a total of 115 papers were selected based on their publication year and their alignment with the research objectives.

1.1.1. *Trend of scientific publication on aluminium matrix composites reinforced with high entropy alloys from 2016 to 2023*

Fig. 1 displays the annual scientific advancements in our understanding of aluminum matrix composites reinforced with high entropy alloys. Based on Scopus, the initial scholarly publication on aluminum matrix composite reinforced with high-entropy alloy (HEA) was published in 2016, with only one paper. In the years 2017, six paper were published while in 2018 with three paper, the only year with decline in the quantity of published articles until now. The number of published papers have experienced a gradual and progressive increase since 2018,

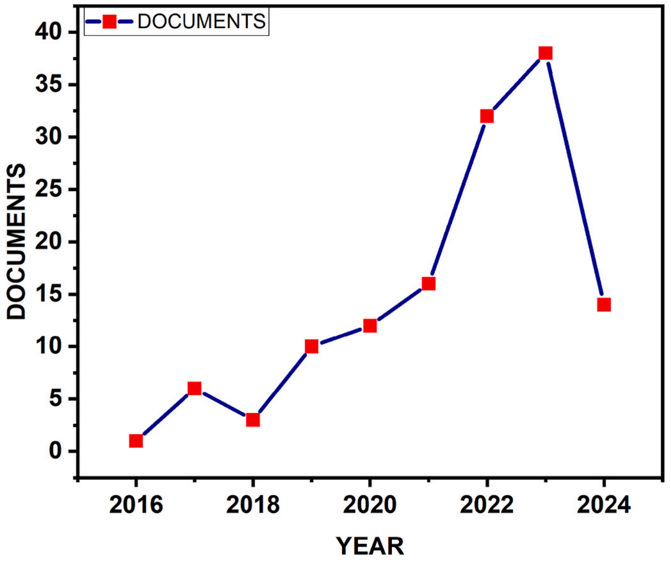

Fig. 1. Trend of scientific publication on aluminium matrix composite reinforced with HEA from 2016 to 2023.

rising from 10 in 2019 to 38 in 2023. In this year 2024, 14 papers have been published from January till March, therefore, it is expected to have more papers published in this year. This upward trend is anticipated to persist as researchers continue to further develop aluminium matrix composites reinforced with HEA.

The country-by-country analysis of publications is presented in Fig. 2, which highlights the noteworthy contributions of 20 different countries to the field of magnesium alloy deformation research. Countries with two or more publications in the Scopus database were considered in this study. The author's global collaboration allowed for the production of identical research papers in several different nations. It is evident from the data in Fig 2 that, with 104 articles overall, China has the largest volume. The following list of nations is arranged according to the amount of articles published: India has 20 articles, Australia has 8, Germany has 6, United Kingdom and Japan have 4, Greece and the United State has 3, South Korea, Romania, Hong Kong, Estonia, Canada and Austria have 2 articles.

The investigation on the aluminium matrix composites reinforced with HEA yielded a limited number of review papers, specifically 0.8%, as depicted in Fig. 3. However, the aforementioned review papers, which accounted for <1% of the total, demonstrated certain limitations in their scope of coverage. These limitations encompassed their corrosion and wear characteristics concerning the HEAs reinforcement, as well as the influence of the matrix/reinforcement interface interactions on their performance assessment. The following section will treat exhaustively the processing and performance evaluation of HEA particles as reinforcements in AMCs.

2. Design and applicability of HEA-particles reinforced aluminium matrix composites

In order to improve the properties of AMCs, particularly strength, hardness, and wear resistance, ceramics have long been recognised as conventional reinforcing materials [10]. The mechanical properties of ceramic-particles reinforced AMCs have yet not attained the desired level due to the weak interfacial bonding caused by the intrinsic brittleness of ceramic systems, as well as differences in the elastic modulus and expansion coefficient at the interface between the ceramic reinforcements and the matrix phase [11,27]. A number of researchers have used metallic glass particles as reinforcing materials in AMCs in an effort to improve their mechanical properties and have achieved limited success [27]. It is observed that metallic glass particles reinforced AMCs are difficult to process owing to their low temperature of recrystallisation and thus not suitable for high-temperature applications [28]. HEAs have a good combination of strength and ductility with exceptional wear, corrosion, and high-temperature properties, which have been linked to their high-entropy and cocktail effects, slow diffusion, and significant lattice distortion [26,29]. Many authors believe that investigating novel reinforcing materials offers the opportunity of improving the functional properties, service performance and thus expand the practical application of AMCs [30–32]. HEA particles have been projected to enhance the matrix/reinforcement interfacial bond which invariably may improve the ductility and toughness of the AMCs [33]. The following discussions will focus on the processing techniques of HEA particles reinforced AMCs and clarify the superiority of HEA particles over traditional reinforcing (ceramic) materials in AMCs in terms of performance reliability in service.

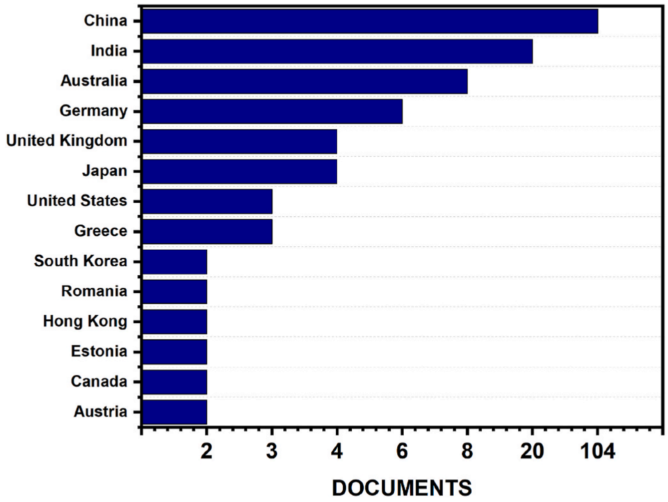

Fig. 2. Document by country or territory with at least 10 published articles in Scopus.

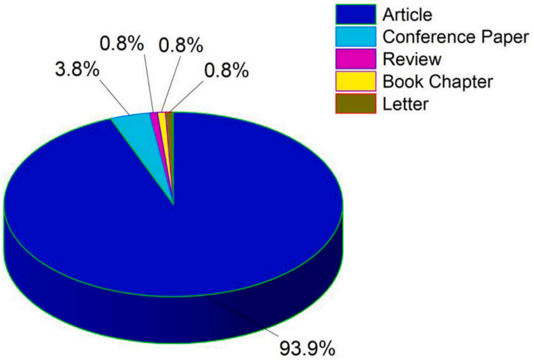

Fig. 3. Document by type in scopus.

2.1. Manufacturing methodology of HEA-particles reinforced aluminium matrix composites

It has been suggested that design and processing approaches are viable options for tuning microstructural characteristics and properties of AMCs [34]. AMCs are manufactured using a variety of fabrication methods that can be divided into two broad categories: liquid metallurgy and solid-phase processing [27]. The classification is based on the procedures for adding reinforcing material [34]. The liquid metallurgy mainly involves the various casting and infiltration processes. In contrast, the solid-phase processing involves the mixing of metal powders with the reinforcing materials followed by the forming process [35]. Depending on the end-use of the AMCs, many authors have employed various techniques, including powder metallurgy [36–38], friction stir powder processing [39,40], shear stress stir casting [41], stir casting [13,42,43], vacuum hot pressing sintering [44], friction deposition technique [45], and ultrasonic casting [45], to produce AMCs. These manufacturing processes have been observed to produce a wide range of microstructural characteristics, which have a significant impact on their functional properties [45].

The influence of the manufacturing process on the mechanical and functional properties of HEA particles reinforced AMCs have been investigated by several authors, including Li et al. [40], Luo et al. [42], Ma et al. [46], and Yuan et al. [47]. Some of these investigations used the powder metallurgy approach, which involves mechanical alloying and/or powder ball milling followed by spark plasma sintering or hot pressing to produce completed or semi-finished HEA particles reinforced composites [37]. Other researchers employed induction melting, injection and dispersion of the reinforcement via stirring, infiltration, squeezing or spraying, and then casting to produce the HEA particles reinforced AMCs products [48]. Li et al. [40] studied the mechanical properties of $Al_{0.8}CoCrFeNi$ HEA particles reinforced AA5083 matrix composite fabricated using the friction stir manufacturing approach. It is evident that the HEA particle addition significantly improved the mechanical properties of the AA5083 aluminium matrix. The yield and tensile strength of the AMCs produced were determined to be 200 MPa and 371 MPa respectively, representing a 42% and 22% increase when compared to the aluminium matrix. No significant change is observed in the ductility of the aluminium matrix after reinforcing with $Al_{0.8}$CoCrFeNi HEA particles. The morphology of the fracture AA5083/$Al_{0.8}$CoCrFeNi HEA particles reinforced composites is characterised by large and deep dimples, which is indicative of a typical ductile failure. It is reported that friction stir manufacturing approach is helpful for achieving an efficient interfacial AA5083/$Al_{0.8}$CoCrFeNi HEA bonding (Fig. 4). In a recent investigation, Luo et al. [42] used the stir casting technique to produce AMCs reinforced with Al0.5CoCrFeNi HEA particles using a liquid metallurgical approach. The AA1050/HEA particles reinforced composite had an ultimate tensile strength of 115 MPa, which represents 74.3% improvement when compared to the strength of AA1050 aluminium alloy those without HEA particles. The ductility in terms of percentage elongation of 32.1% is obtained for the AA1050/HEA particles reinforced composite.

Ma et al. [46] studied the interfacial interactions and mechanical behaviour of $Al_{0.6}$CoCrFeNi/5052Al matrix composites manufactured using the vacuum hot-pressing sintering process. The mechanical behaviour of the composite is strongly dependent on the thickness of the intermetallic compound of $Al_{13}Co_4$-, Al_9Co_2-, and $Al_{18}Cr_2Mg_3$ phases formed as a result of diffusion at the $Al_{0.6}$CoCrFeNi/5052Al interface. Compressive strength and hardness of the composite were higher than those of the matrix. The composites attained maximum values of 345.7 MPa for compressive strength and 82.8 HV for hardness after annealing treatment at 500 °*C* for 5 h. Yuan et al. [47] in a related study carried out on the structural and mechanical properties of CoCrFeMnNi HEA particles reinforced 2024Al matrix processed by spark plasma sintering (SPS) technique. The hardness of the composite material is 131 HV which represents about 63.7% increase when compared to the hardness of aluminium matrix. The increase in hardness of the composite is attributed to the formation of an intermetallic diffusion layer of about 6 μm in thickness. It is evident that the atoms in the diffusion layer diffuse equally throughout the SPS process.

The formation of a gradient interface microstructure is advantageous as it lessens stress concentration at the interface and enhances the composite's bearing capacity and stress distribution state. The study observed that the SPS process facilitates the formation of fine dispersion of the HEA particles in the matrix structure of the composite. As a result of the fine dispersion of the HEA particles in the matrix and the CoCrFeMnNi HEA particles/2024Al matrix interface, dislocations are impeded from moving freely and become plugged. This increases the resistance to deformation of the composite, and ultimately, the hardness and strength of the material equally increase.

Yang et al. [39] studied AlCoCrFeNi HEA particle-reinforced 5083Al matrix composites produced by the submerged friction stir method. It is observed that the composites manufactured by the submerged friction stir method showed 25.1% and 31.9% increase in the yield and tensile strength respectively, when compared to the aluminium matrix. This result is in agreement with the findings of Chitturi et al. [49] and Gao et al. [50] where friction stir processing techniques were used to produce 6061Al/FeCoCrNiMo and 5083Al/FeCoNiCrAl AMCs, respectively. These authors noted that the varying volume fraction of the HEAp reinforcement had significant impact on the overall mechanical properties of the composites. The HEAp reinforcement led to improvement in the strength, however, with marginal reduction in the plasticity, thereby, resulting to a good strength/ductility balance of the produced composites. It is widely reported that the properties of HEA particles reinforced AMCs are superior to those of the aluminium matrix irrespective of the fabrication process adopted [43,51,52].

Additive manufacturing techniques have been reported to produce a rapid solidification effect, enhance microstructural homogeneity, and improve the properties of AMCs [53]. HEA particles reinforced AMCs built by additive manufacturing exhibit superior functional properties when compared to their counterparts manufactured by the conventional casting process [54]. Karthik et al. [52] studied CoCrFeNi HEA particles reinforced AA5083 aluminium matrix composite built by additive manufacturing. The intermetallic layer formed at the reinforcement/matrix interfaces exhibits a ductile characteristics (see Fig. 5), which provided a far superior combination of ductility and strength than aluminium matrix. HEA particle being a deformable particle has the capability to undergo substantial yielding before fracture and this lead to enhanced strength-ductility ratio, unlike the brittle ceramic particle that undergoes little or no yielding before fracture. Friction deposition additive manufacturing process demonstrated a practical method for producing innovative, high-performing AMCs reinforced with HEAs. Research has continued to explore new additive manufacturing techniques in pursuit of quality and high-performance AMCs products [55].

A thorough comparison of the various processes involved in the fabrication of HEA particles reinforced AMCs has been detailed elsewhere [56,57]. It can be deduced from the works reviewed thus far that

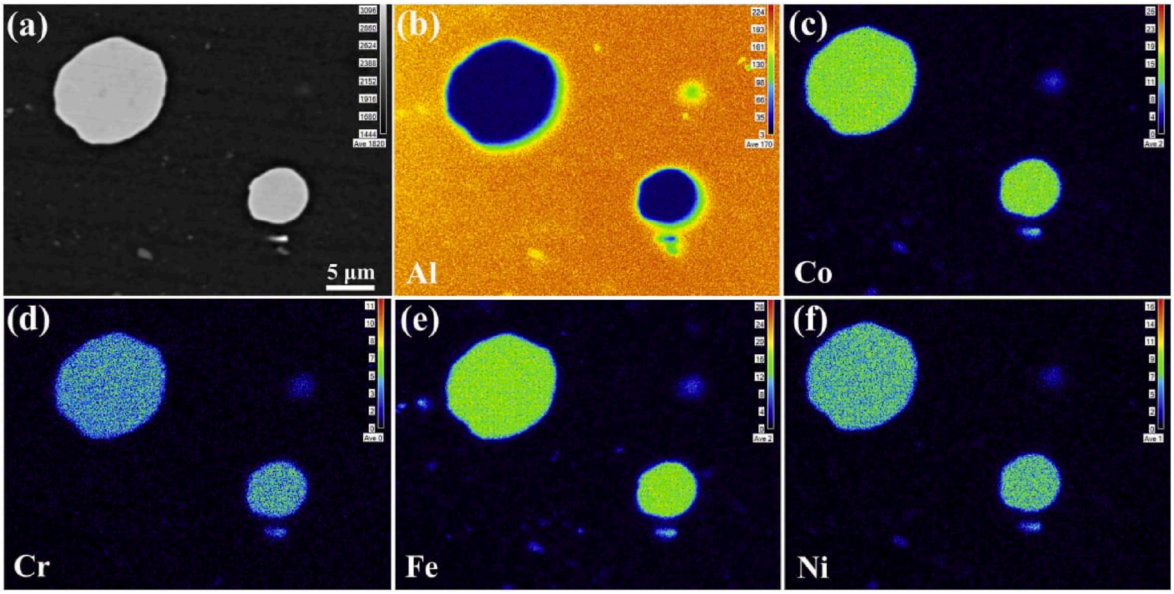

Fig. 4. (a) Interfacial morphology and (b–f) element distribution of Al, Co, Cr, Fe and Ni in the FSPed AMCs [40]. Culled with permission from Elsevier.

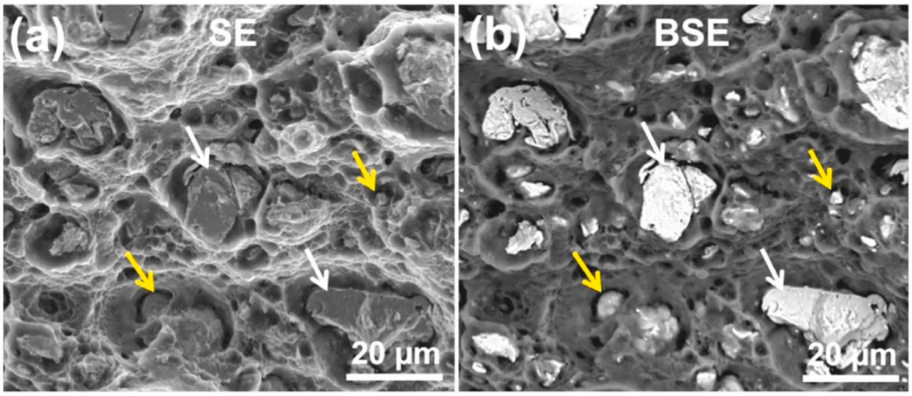

Fig. 5. (a) SEM - SE image of the fracture surface of a single-layer composite tensile specimen. Its corresponding BSE image is shown in (b), which clearly reveals the HEA particles in bright contrast. White arrows show sheared or ruptured HEA particles. Yellow arrows show fine HEA particles inside the dimples [52]. Culled with permission from Elsevier. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the improvement in the mechanical properties of HEA particles reinforced AMCs is related to the characteristics of the diffusion layer formed at the Al/HEA interface. HEA particle being a deformable particle has the capability to undergo a substantial yielding before fracture and this lead to enhanced strength-ductility ratio, unlike the brittle ceramic particle that undergoes little or no yielding before fracture and this leads to low strength-ductility ratio. The following section will address the microstructural interaction between the matrix and reinforcement phases, which can provide insight into how HEA particles enhance the functional properties of the composites.

2.2. HEA particles interaction and evolution of interfaces in HEA particles reinforced AMCs

It is widely reported in the literature that ceramic reinforcements in AMCs improves their mechanical properties at the expense of ductility due to the brittle character of the interfacial diffusion layer formed at the matrix/reinforcement boundary [58]. Metallic reinforcements on the other hand, have been shown to exhibit good wetting and bonding characteristics at the matrix/reinforcement interface, which results in a significant improvement in the ductility, compared to their counterparts reinforced with ceramic materials [59]. Recently some authors have implemented HEA particles as reinforcing materials in AMCs and achieved obtained a good combination of mechanical strength and elongation owing to the ductile character of the intermetallic compounds formed at the matrix/reinforcement diffusion layer [39,49,50]. In order to further improve the reliability and product performance of AMCs, it is critical to elucidate the mechanisms of their matrix/reinforcement interactions and their products in relation to the evolved microstructures.

The geometry of the reinforcing material, structural and chemical characteristics of the intermetallic compounds formed the diffusion layer of matrix/reinforcement boundary has strong influence on their properties [47,60]. It has been reported that the boundary layer between the reinforcing material and the matrix is a weak zone which serves as preferential sites stress concentration and crack initiation [61]. Several authors, including Ma et al. [46], Gao et al. 62], Huang et al. [63], Li et al. [13], Yang et al. [39], and Li et al. [7], have studied the interface interactions and evolved microstructures in HEA particles reinforced AMCs.

When producing aluminium matrix composites, the interactions between the reinforcement additions and the matrix alloys—including kinetic diffusion and thermodynamic reactions—are essential for regulating the composites' final microstructure and interfacial strength. A specific number of reactions might enhance the process of interfacial wetting during processing and bonding in the resulting solidification products. Nevertheless, an overabundance of reactions might result in the creation of brittle intermetallic phases at the interfaces between the matrix and particles, which ultimately diminishes the functionality of the composites. Ma et al. [46] studied the interfacial properties as well as the mechanical behaviour of $Al_{0.6}CoCrFeNi$ HEA particle reinforced Al-matrix (5052Al) composite produced by vacuum hot-pressing sintering process. The structural composition of the composite consists of the Al-matrix, diffusion layer composed of variant intermetallic compounds, and fine particles of $Al_{0.6}CoCrFeNi$ HEA reinforcement. The study observed that the formation of intermetallic compounds that emerged in the diffusion layer of the HEA particles/Al-matrix interface was a solid-state reaction which occurs by volume diffusion mechanism. The diffusion layer's thickness exhibits a parabolic relationship with the annealing time as seen in Fig. 6. A stable metallurgical bond was formed at the interface between the HEAp and Al matrix, resulting in the formation of the diffusion layer. This bond is crucial for load transfer. The composite's compressive strength exhibited a progressive increase when the thickness of the diffusion layer was increased during the initial phase of the annealing process. Nevertheless, with the progressive increase in annealing temperature or duration, the thickness of the diffusion layer exhibited a corresponding increase. Consequently, the edges of the particles underwent gradual dissolution, leading to the total diffusion and subsequent disappearance of certain HEAp. Consequently, this phenomenon resulted in a reduction of the load-carrying capacity of the reinforcement.

Furthermore, the intermetallic compounds of $Al_{13}Co_4$-, Al_9Co_2-, and $Al_{18}Cr_2Mg_3$ phases were formed as a result of diffusion at the $Al_{0.6}CoCrFeNi$/5052Al interface had significant effect on the yield strength. The hard and brittle intermetallics prevent the slip of dislocations during compressive deformation, causing an increase in deformation resistance and leading to an increase in YS. However, an excessive increase in the brittle phase in the interface region promotes the sprouting and expansion of cracks; thus, the YS of the composites also decreases sharply when the thickness of the diffusion layer exceeds a certain range (<10 μm). Therefore, the strength of the composite is strongly dependent on the diffusion layer's thickness, which increases with annealing treatment time and temperature.

Gao et al. [62] studied FeCoCrNiAl HEA particles that reinforced 7075Al matrix (HEAp/Al) composites produced using vacuum hot pressing sintering. The structural morphologies of the evolved microstructures at the interface between the reinforcing HEA particles and the Al-matrix varied with the concentrations of the reinforcements. The composites having reinforcements in the concentration range of 5–10 vol percentage exhibited a uniform dispersion of the reinforcements in the matrix structure. At 15 and 20 vol percentages of the reinforcements, the microstructure is characterised by severe heterogeneous reinforcement's dispersion in the matrix structure. Agglomeration tendency increases with an increase in the volume percentage of the reinforcement. It is observed that when the reinforcement concentration

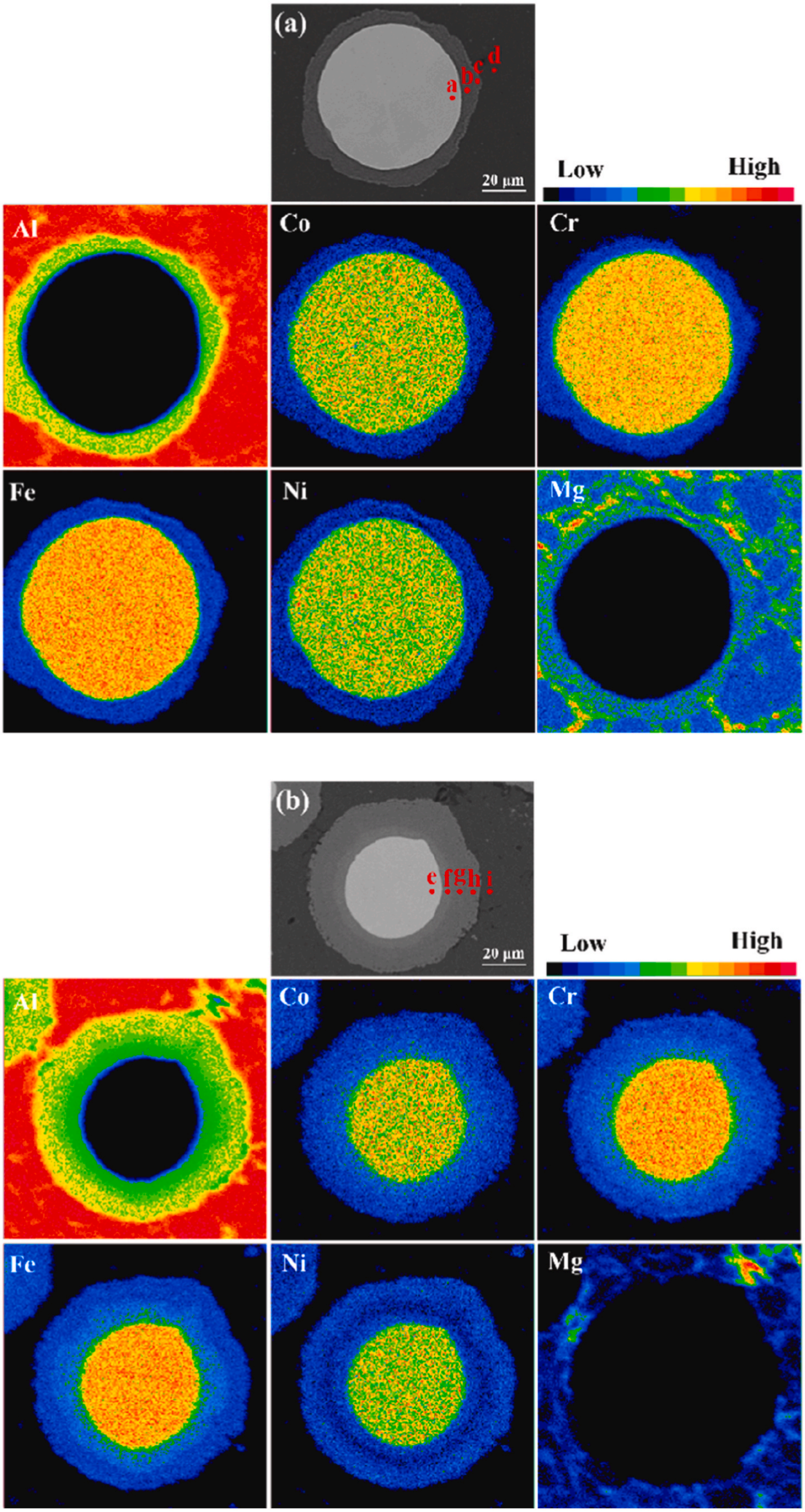

Fig. 6. Elemental mapping of composites annealed at 773 K for different annealing times (a) 24 h, (b) 96 h [46].Culled with permission from Elsevier.

surpassed 12.87 vol %, particle coagulation in the matrix became significant. The energy dispersive x-ray spectroscopy (EDS) live mappings of the constituent elements: Al, Co, Cr, Ni, Fe, and Mg at the interface between HEA particle and 7075Al matrix established an evident boundary at the interface. This report is in agreement with the observations of Huang et al. [63], where the structural characteristics of the AlCrTiV HEA particle-reinforced 7075 aluminium matrix composite is studied.

Varying weight percentages of reinforcing HEA particles is dispersed into Al melt and the composite is produced via ultrasonic-assisted casting process. The microstructural evolution at the HEA particle/aluminium matrix interface is shown in Fig. 7. Particles of the HEA reacts with the aluminium melt to form $Al_{45}(Cr,V)_7$ phase, which disperses in the Al-matrix (Fig. 7a). $Al_{45}(Cr,V)_7$ and Al_3Ti intermetallic phases were found to have formed at the reinforcement/matrix diffusion layer as a result of a reaction between the AlCrTiV HEA particles and molten aluminium matrix as seen in Fig. 7b. The results showed that the AMCs formed contained no original B2-structured AlCrTiV HEA particles, whereas the evolved microstructural characteristics of the composites largely depend on the interactions between the particles and matrix aluminium alloys.

The diffusivity of elements (such Cr and Ti) in liquid aluminium is clearly several orders of magnitude higher than that of solid aluminium. Hence, despite the limited duration of exposure to molten aluminium, the AlCrTiV HEA particles underwent complete transformation into intermetallic phases. Hence, it was concluded that the Al45(Cr, V)7 and Al3Ti phases, in contrast to most ceramic particles, exhibit enhanced coherence at their interfaces with the aluminium matrix. Consequently, this leads to superior wetting characteristics during the solidification process and notably enhanced mechanical properties in the composite materials. The obtained refined grains in the composite's microstructure, the exceptional wetting that occurred during solidification, and the strengthening caused by the dispersed high entropy alloy particles all contributed to the composite's increased mechanical strength.

Huan et al. [64] studied the mechanical properties of $AlFeNiCrCoTi_{0.5}$ HEA particles reinforced 6061 aluminium matrix composite fabricated by cold isostatic pressing and extrusion process. Scanning electron microscopy was used to analyse the microstructures of the AMCs. No distinct precipitates appeared at the interface between AlFeNiCrCoTi0.5 and the Al matrix, but the elements within the high-entropy alloys (HEAs) demonstrated uniform distribution. The introduction of the Al element resulted in an augmentation of the BCC structure development and a reduction in the FCC structure, hence resulting in an enhancement of the material's strength. The HEA particles although uniform distributed, exhibited cracks resulting from mechanical alloying, hence diminishing the overall strengthening efficacy. Defects in the matrix structure are observed to increase with the increase in volume percentage of the HEA particles reinforcement. The optimum properties and strengthening effect are achieved with a 10% volume of the HEA reinforcement, which results in a hardness of 70.3 HV, tensile strength of 188.1 MPa, and elongation of 14.1%. Unfortunately, strength is lost due to agglomeration of the reinforcing HEA particles in the matrix structure, which happens when the reinforcements is up to 15 vol % or above.

Li et al. [40] investigated the microstructural characteristics and tensile strength of $Al_{0.8}CoCrFeNi$ HEAp reinforced AMCs produced by multiple friction stirring process. Because the Al matrix and the HEA reinforcements combined have outstanding physical metallurgical compatibility, it was observed that the interfacial regions between the Al matrix and the integrated HEA particles are continuous and compact. Moreover, the effective interfacial bonding was facilitated by the adequate material flow during the multi-pass friction stir processing (FSP). The diffusion of Al atoms between the interfaces of Al and HEA was established to have led to the emergence of an Al transition layer with a thickness of less than 1.0 μm. Fig. 8 displays the fractographs of the FSPed samples. The fracture morphology observed in both the FSPed Al alloys and the FSPed AMCs exhibited characteristic ductile failure, characterised by the presence of prominent and profound dimples. The HEAs particles that have been integrated are situated at the lower section of the dimples, exhibiting no signs of breakage or detachment (as seen in Fig. 8c). This observation suggests a strong and compact interfacial connection between the aluminium matrix and the HEAs particles. Meanwhile, it has been demonstrated that the inter-diffusion layers play a favourable role in enhancing the effectiveness of interfacial bonding.

According to the study, Co, Cr, Fe, and Ni atoms diffuse from HEA particles toward the Al matrix and vice versa, resulting in a diffusion layer at the interface between the reinforcement and the matrix. The structural characteristics of the diffusion layer have a strong influence on the properties of the AMCs. The increase in mechanical characteristics can be attributed to the combined influence of the minute diffusion layers, the substantial grain refinement, and the uniformly distributed reinforcements.

Yang et al. [39] studied the microstructure and mechanical behaviour of AlCoCrFeNi HEA particles reinforced 5083 Aluminium matrix composite fabricated by the submerged friction stirring process. The microstructures of the produced composites were characterised by equiaxed, fine grains formed due to the occurrence of dynamic recrystallisation by particle-stimulated nucleation mechanism. The AMCs had finer structures compared to the microstructure of 5083 Aluminium formed by the submerged friction stirring process. Fig. 9 shows the transmission electron microscopy image of the microstructural features of the diffusion layer at the HEA/Al-matrix interface. A dual interface diffusion layer at the HEA particle/5083 Al matrix interface is observed; one near the HEA particles consisting of FCC + T-phases with a layer thickness of 100 nm, while the other near the Cr-depleted AlCoCrFeNi HEA particles also has a thickness of 100 nm. The character of these

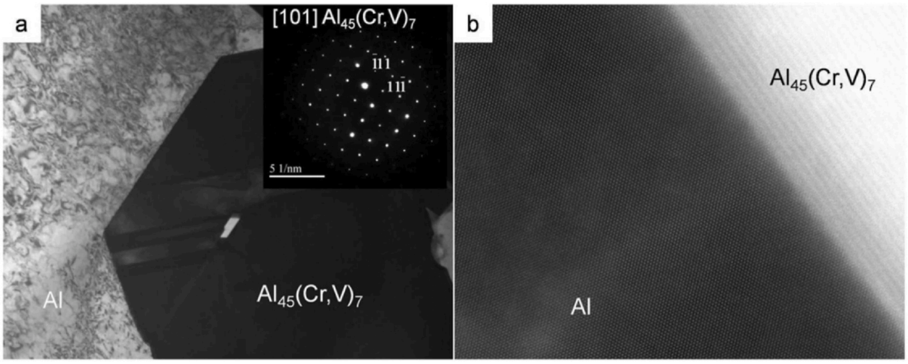

Fig. 7. Results of scanning/transmission electron microscopy (STEM/TEM) for 3 wt% HEA particle reinforced Al-matrix. (a) Bright-field TEM image and the diffraction pattern along [101] zone axis of $Al45(Cr,V)_7$ diffusion layer. (b) STEM image of the $Al45(Cr,V)_7$ HEA reinforcement/Al-matrix interface [63]. Culled with permission from Elsevier.

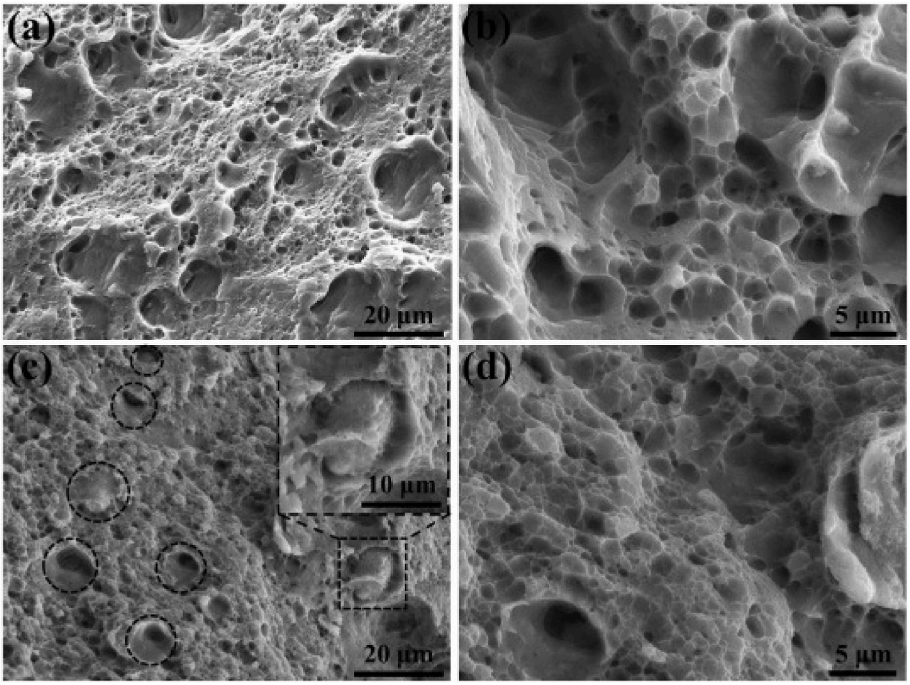

Fig. 8. Fractographs for (a, b) the FSPed Al alloys and (c, d) the FSPed AMCs.

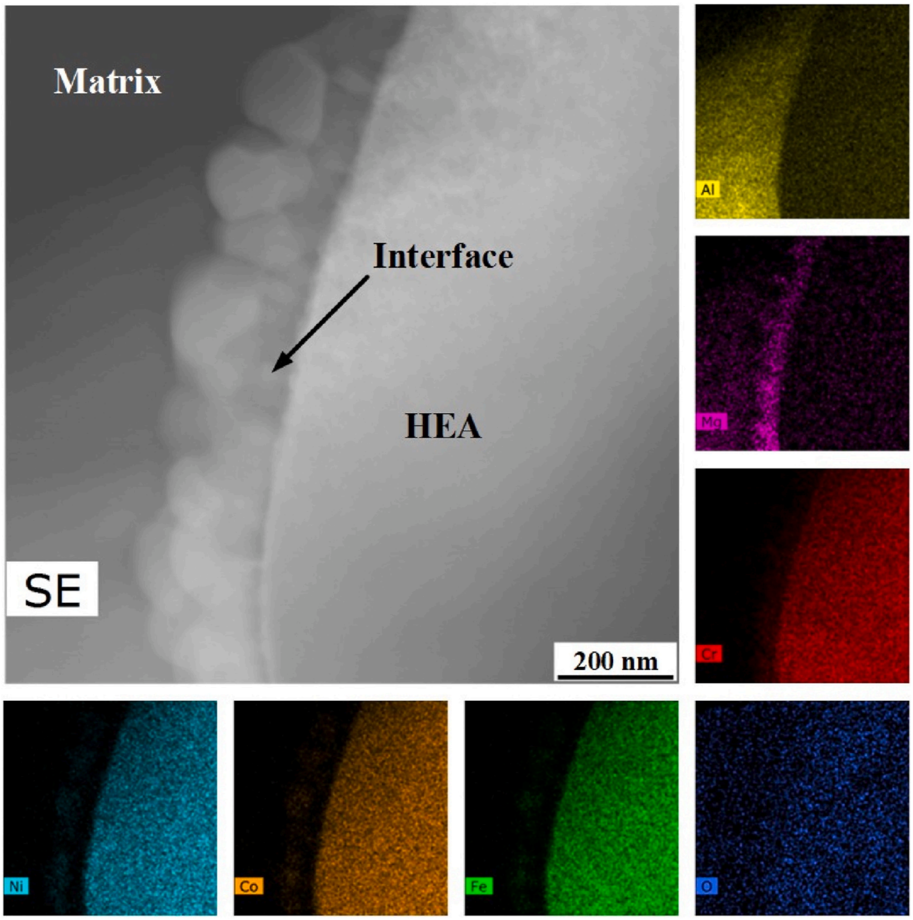

Fig. 9. Transmission electron microscopy image of the HEA/Al-matrix interface and live mapping of the constituent elements [39]. Culled with permission from Elsevier.

diffusion layers is responsible for the observed improvement in the strength and ductility of the AMCs in relation to the Al-matrix.

Yang et al. [65] studied the interfacial structural properties and mechanical behaviour of AlCoCrFeNi HEA particles reinforced AMCs produced by spark plasma sintering process. The HEA particles were evenly distributed at 5 vol% and 10 vol% reinforcements. However, at 15 vol% reinforcement, there was evident particle aggregation, and the microstructure is characterised by heterogeneous overlapping of the reinforcement/matrix interface reaction layer. The results indicate there is loss of strength beyond 10 vol% reinforcement. The SEM/TEM images of the HEA/Al-matrix interface characteristics of the AMCs are presented in Fig. 10. There are two layers in the interface structure: $Al_{13}(CoCrFeNi)_4$ was the interface reaction layer near the HEA particles (layer I). At the same time, $Al_9(CoFeNi)_2$ and $Al_{18}Cr_2Mg_3$ made up the interface reaction layer at the Al matrix (layer II). The incorporation of HEA particles resulted in an augmentation of the yield strength, while concurrently diminishing the tensile strength and elongation of the composites. The rapid failure of composites can be related to the aggregation of HEA particles and the overlaying of the HEA-Al interface reaction layer, which facilitates the initiation and propagation of cracks in this region. The tensile fracture mechanism of the AMCs was attributed to the aggravating degree of stress concentration at the interface diffusion layer near the HEA particles and the poor plasticity of the $Al_{13}(CoCrFeNi)_4$ phase in the matrix structure. The character of the interface reaction products thus affects the tensile properties of the composite. When compared to the Al-matrix, the HEA particles improved the tensile properties of the AMCs.

Numerous findings about the impact of an interfacial layer on the functionality of AMCs have been documented [13,30,44,66]. It can be deduced from these studies that HEA particles at the interface between the reinforcement and the Al matrix, show exceptional wettability. Observations showed that a ductile interfacial layer formed as a result of a diffusion interaction between the Al-matrix and the HEA particle interface. The diffusion layers that exist at reinforcement/matrix boundary are formed by the mechanism of volume diffusion and the thickness of the diffusion layer is temperature and time-dependent. The interface bonding strength, interface reaction products and the morphology of the HEA particles are prominent factors that determine the functional properties of the AMC. It can be construed that the use of HEA particles as reinforcing materials in AMCs results in a good combination of strength and ductility while outperforming ceramic reinforcing materials. This suggests that a proper interfacial diffusion layer can be designed to improve the performance of AMCs. The microstructural characteristics of the diffusion layer at the aluminium-matrix/HEA reinforcing particles interface are summarised in Table 1.

3. Mechanical behaviour of aluminium matrix composite reinforced with HEA-particles

Al_2O_3, SiC, TiB_2, and B_4C are a few examples of ceramic reinforcements that are frequently used as reinforcement materials in AMCs due to their enhanced strength, stiffness, and corrosion resistance [67]. The enhanced stress transfer from the matrix phase to the reinforcing phase results in a strengthening effect by dislocation and grain boundary strengthening [68,69]. However, the main disadvantages of AMCs made with ceramic reinforcements are the poor wetting characteristics between the matrix and the reinforcement, agglomeration of the reinforcement, and the brittle nature of these ceramic systems which resulted in their poor fracture toughness and low ductility [51]. It is also reported that the large difference in the coefficients of thermal expansion between the metallic matrix and ceramic reinforcements accounts for their poor workability [51]. Researchers have considered metallic glasses as reinforcement to address the inadequacies of ceramic reinforcement since they have a better bonding strength with the AMCs than ceramic reinforcements [70,71]. Their utilization is limited to low-temperature service conditions because of their low crystallisation temperature [71]. HEA particles have been envisaged to perform better than ceramics and metallic glasses when utilized as reinforcements in AMCs due to their exceptional strength-ductility ratio and high-temperature strength [49]. In the succeeding sub-sections, the properties and service performance of AMCs reinforced with HEA particles are discussed in different categories based on their method of production.

3.1. Liquid metallurgy approach

Many authors, including Chitturi et al. [49], Lu et al. [72], and Li et al. [7], have evaluated the performance of HEA-particles reinforced AMCs manufactured by the casting process. Chitturi et al. [49] studied

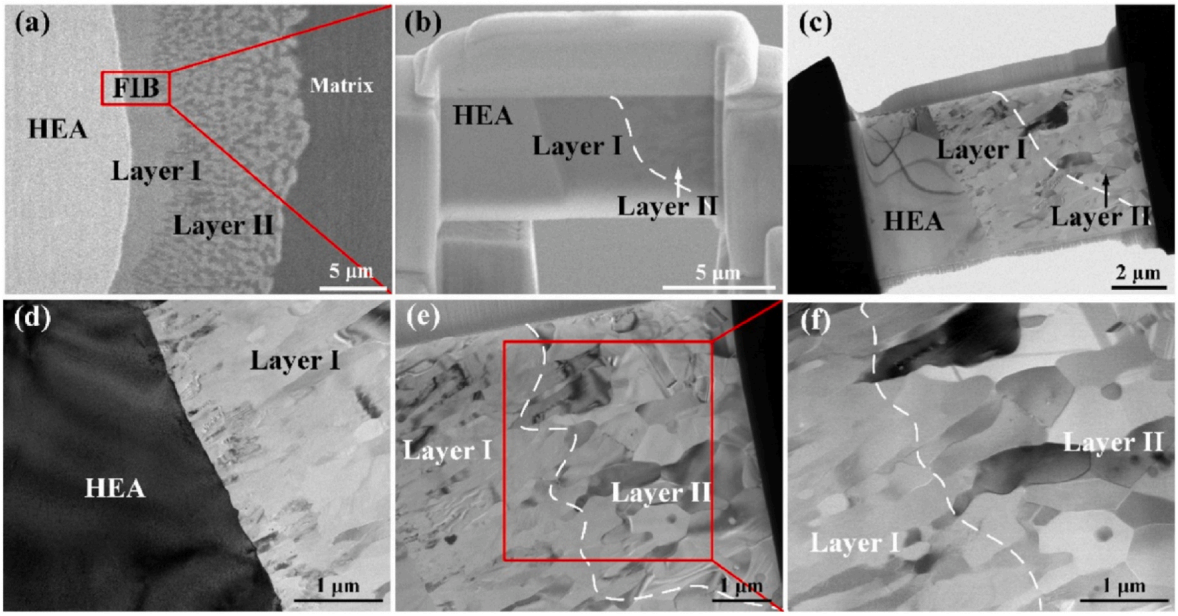

Fig. 10. SEM/TEM images of the Interface characteristics of the HEA/Al-matrix composite (a) SEM image, (b) foil examined by SEM, (c) foil examined by TEM, (d–f) TEM images of the HEA/Al-matrix interface [65]. Culled with permission from Elsevier.

Table 1
Summary of the microstructural characteristics of the diffusion layer at the aluminium-matrix/HEA reinforcing particles interface.

Aluminium Matrix Composites	Fabrication Process	Microstructural Characteristics at the Al-matrix/HEA-particles Interface	Reference
5052 Al matrix reinforced with $Al_{0.6}$CoCrFeNi HEA particles	Vacuum hot pressing sintering process	Intermetallic compounds are formed in the diffusion layer of the HEA particles/Al-matrix interface by volume diffusion mechanism. The thickness of the diffusion layer exhibits a parabolic relationship with the annealing time. The diffusion layer is composed of $Al_{13}Co_4$-, Al_9Co_2-, and $Al_{18}Cr_2Mg_3$ phases formed as a result of diffusion at $Al_{0.6}$CoCrFeNi/5052Al interface.	[46]
7075 Al matrix reinforced with FeCoCrNiAl HEA particles	Vacuum hot pressing sintering process	A clear diffusion layer appeared at the boundary between the HEA-particles and the Al-matrix. Agglomeration tendency increases with increase in volume percentage of the reinforcement with the optimum at 12.87 % vol. reinforcement. Dislocations occur at the HEA-particles/matrix interface due to the disparity in between the coefficient of thermal expansion between the HEA particles and the 7075 Al matrix.	[62]
6061 Al matrix reinforced with AlFeNiCrCo$Ti_{0.5}$ HEA particles	Cold isostatic pressing and extrusion process	No distinct precipitates were seen at the interface between AlFeNiCrCoTi0.5 and the Al matrix, but the elements within the high-entropy alloys (HEAs) exhibited uniform distribution. The introduction of the Al element increased the BCC structure development and a reduction in the FCC structure, hence resulting in an enhancement of the material's strength. The HEA particles exhibited uniform distribution, although exhibited cracks resulting from mechanical alloying, hence diminishing the overall strengthening efficacy. 10 vol% HEA particles reinforcement yielded the optimum strength and ductility due to the attendant fine distribution of the reinforcements in the matrix structure.	[64]
5083 Al matrix reinforced with AlCoCrFeNi HEA particles	Spark plasma sintering process	A clear diffusion layers appeared at the boundary between the HEA-particles and the Al-matrix. There are two layers in the interface structure: $Al_{13}(CoCrFeNi)_4$ was the interface reaction layer near the HEA particles, while $Al_9(CoFeNi)_2$ and $Al_{18}Cr_2Mg_3$ made up the interface reaction layer at the Al matrix. The character of the diffusion layer determines the tensile behaviour of the AMCs. $Al_{13}(CoCrFeNi)_4$ phase is characterised with poor plasticity.	[65]
5083 Al matrix $Al_{0.8}$CoCrFeNi HEA particles	Friction stir process	Co, Cr, Fe, and Ni atoms diffuse from HEA particles toward the Al matrix and vice versa, resulting in a diffusion layer at the interface between the reinforcement and the matrix. The HEA particles caused a 50% reduction of the matrix structure by particle simulation nucleation mechanism.	[40]
5083 Al matrix reinforced with 10 vol % AlCoCrFeNi HEA Particles	Submerged friction stir process	A dual interface diffusion layer at the HEA particle/5083 Al matrix interface is observed; one near the HEA particles consisting of FCC + T-phases with a layer thickness of 100 nm, while the other near the Cr-depleted AlCoCrFeNi HEA particles also has a thickness of 100 nm. Grain refinement by dynamic recrystallisation mechanism occurs in the AMCs.	[39]
5052 Al matrix reinforced with 7 vol% of $Al_{0.6}$CoCrFeNi HEA particles	Vacuum hot pressing sintering process	Pronounced diffusion layer exists at the boundary between the HEA reinforcement particles and the Al-matrix. The HEA are distributed in the Al-matrix and react with the matrix to form an intermetallic diffusion layer, and the thickness is a function of the heat treatment time.	[44]

(*continued on next page*)

Table 1 (*continued*)

Aluminium Matrix Composites	Fabrication Process	Microstructural Characteristics at the Al-matrix/HEA-particles Interface	Reference
2024 Al matrix SiC and $CoNiFeCrAl_{0.6}Ti_{0.4}$ HEA particles	Powder metallurgy	An interface diffusion layer composed of Al, Cu, Co, and Ni with a thickness of 200 nm is formed at the HEA-particles/matrix interface.	[66]

the mechanical behaviour of a hybrid FeCoCrNiMo HEA and B_4C-reinforced AMCs produced by the stir casting method. It is observed that the strength of the hybrid AMCs showed a considerable increase with the increase in the volume percentage of the HEA-particles. The composites produced from 3 wt% HEA-particles and 1 wt% B4C hybrid reinforcement showed the optimum performance with 29%, 11.8%, and 25.3% increase in the tensile strength, toughness, and hardness when compared to the properties of the Al-matrix. It is reported that the fracture toughness of the composites is higher than that of the unreinforced Al alloy. The fracture toughness of the composites increase with increase in the HEAp addition.

The addition of HEAp at 1 wt%, 2 wt%, and 3 wt% increments leads to an increase in the fracture toughness of the composites. Specifically, there is a percentage increment of 1.8%, 8%, and 11.8% respectively compared to the pure Al alloy.The improvement was as a result of the strong interfacial bonding between the matrix and reinforcement particles which leads to improved load transfer between the matrix and the reinforcement phase. The addition of HEAp help to increase the nucleation rate and decrease the grain size which in turn enhance the strength metrics. Similar result is reported by Lu et al. [72] where the mechanical properties of SiC and $CoNiFeAl_{0.4}Ti_{0.6}Cr_{0.5}$ HEA particles reinforced 7075 Aluminium matrix composites processed by squeeze casting method. It is observed that the Al/HEA-particles composite has a maximum strength of 712 MPa, Young's modulus of 171 GPa, and plasticity of 0.82%, which were considerably higher compared to the values obtained for the Al/SiC composite. It is explained that the HEA-particles reinforcements resulted in better reinforcement/matrix interface and dislocation density, which accounts for their superior strength and ductility properties relative to AMCs reinforced with SiC.

Li et al. [7] studied the properties of AlFeNiCrCoTi HEA-particles reinforced Al-matrix composite fabricated by the casting process. The study observed that the best combination of tensile properties is achieved at 5 vol % HEA-particles reinforcement, yielding an ultimate tensile strength of 170 MPa and a percentage elongation of 22.7%. The composites showed superior properties when compared with the Al-matrix. This is due to the solid solution strengthening as a result of Ti and Cr dissolution in aluminium matrix, fine grain structures and the precipitated blocky Al–Ti–Cr and flaky Al_3Ti intermetallic phases, which were formed in the Al-matrix due to the interaction between the matrix and the reinforcing HEA-particles. Dimples were present in the fracture morphology of the composite, which suggests that the composite failed under tension in a ductile manner. At 6 vol%HEAp addition the hardness value increased by 184.8% compare to the unreinforced Al alloy, which is as a result of the increase in the hard intermetallic phases formed in the composite. However, there was marginal reduction in the UTS and the elongation values, this was associated to the high increase of the flake-like Al_3Ti and blocky Ai–Ti–Cr intermetallic compounds with the hard and brittle properties leading to the local stress concentration. On the other hand, the interfacial bonding strength is weakened between the intermetallic compounds and the matrix. Hence, more research should be carried out on the evolution of intermetallic phases in Al/HEAp composites.

In a recent study, Luo et al. [73] studied the mechanical behaviour of CoCrFeNiAl HEA-particles reinforced 1050Al-matrix composite produced by the stir casting process. The cast composites were subjected to asymmetric rolling (AR) and asymmetric cryorolling (ACR) processing with rolling reduction ratios of 50%, 80%, and 95%. It is observed that the hardness, yield strength, and tensile strength of the AMCs increase with the increase in HEA-particles reinforcement up to 3 wt %. The yield strength of the composites before and after the various rolling operations at different degrees of deformation (0%, 50%, 80%, and 95%) is presented in Fig. 11. It is observed that the asymmetric cryorolling process effectively improves the properties of the composites compared to those of their counterparts subjected to the asymmetric rolling process. At 3 wt % HEA-particles reinforcement and rolling reduction ratio of 80%, the yield strength of the ACR samples improved to 213 MPa compared to 195 MPa and ≈ 70 MPa obtained for the AR and as-cast samples.

At a rolling reduction ratio of 80% for instance, the ultimate tensile strength (UTS) of the as-cast HEA-particles reinforced AMCs was 115 MPa; and it was significantly raised to 207 MPa and 231 MPa after AR and ACR treatments respectively. The strength of the composites is observed to increase with the increase in the percentage of rolling reduction as the UTS of the ACR samples rose to 253 MPa after a 95% rolling reduction. The improved strength of the samples subjected to the ACR process is attributed to the following strengthening mechanisms: mismatch strengthening, fine grain strengthening, and Orowan strengthening. The strength of HEA-particles reinforced AMCs can reach a maximum value of 253 MPa which is superior when compared to 100–120 MPa for rice husk ash plus Al_2O_3 reinforced AMCs [74], 120–180 MPa for SiC reinforced AMCs [75], 130–150 MPa for $Si0_2$ reinforced AMCs [76], and 100–110 MPa for carbon fibre reinforced AMCs [77]. HEA particle being a deformable particle has the capability to undergo substantial yielding before fracture, unlike the brittle ceramic particle that undergoes little or no yielding before fracture. The microstructural characteristics after AR and ACR processes are shown in Fig. 12. It is observed that the microstructure of ACR samples is characterised by heavy dislocation networks, subgrains and finer grain structures compared to the AR images. The study suggests that the mechanical properties and microstructure of the HEA-particles reinforced AMCs is significantly enhanced by the ACR procedure.

Huang et al. [63] reported that the yield strength and ultimate tensile strength of the AlCrTiV HEA-particles reinforced AMCs were both markedly enhanced by the intermetallic $Al_{45}(Cr,V)_7$ and Al_3Ti phases that evolved at the diffusion layer of the composites. The observed reduction in grain size and consequent improvement in mechanical characteristics are caused by the reinforcing particles, which serve as heterogeneous nucleation sites during solidification.

Verma and Singh [78] also observed significant improvements in the hardness, ultimate tensile strength and yield strength with the additions of CoMoMnNiV HEA particles as reinforcement in Al7075 matrix composite. The observed phenomenon can be attributed to the strengthening impact exerted by the strong metallic high-entropy alloy (HEA) particles on the molten aluminium. The HEAp reinforcement and the interfaces between the aluminium matrix substantially influenced the tensile strength of the composite, mostly due to the strong interfacial bonding. The uniformly distributed high-entropy alloy (HEA) particles, consisting of cobalt, molybdenum, manganese, nickel, and vanadium, within the composite of the aluminium alloy, served as an obstacle to the movement of dislocations in the matrix alloy, hence thwarting fracture. Nevertheless, the inclusion of HEA particles resulted in a little decrease in the elongation of the generated composites compared to the base alloy.

3.2. Powder metallurgy processes

Because of their remarkable high-temperature properties and good strength-to-ductility ratio, HEA particles are gaining more attention as reinforcing materials in AMCs than metallic glass, ceramics,

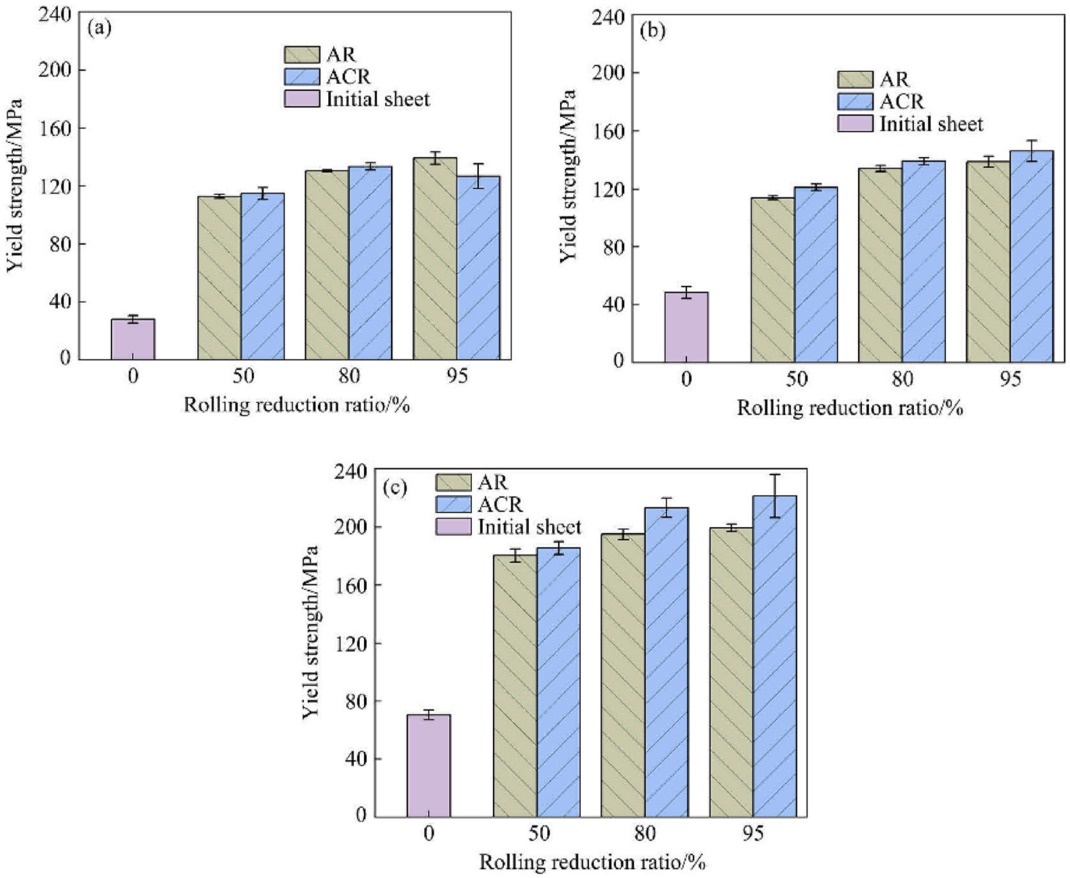

Fig. 11. Yield strength of the initial sheet (as-cast), AR, and ACR samples for: (a) 0 wt% HEAp; (b) 1 wt% HEAp; (c) 3 wt% HEAp [73]. Culled with permission from Elsevier.

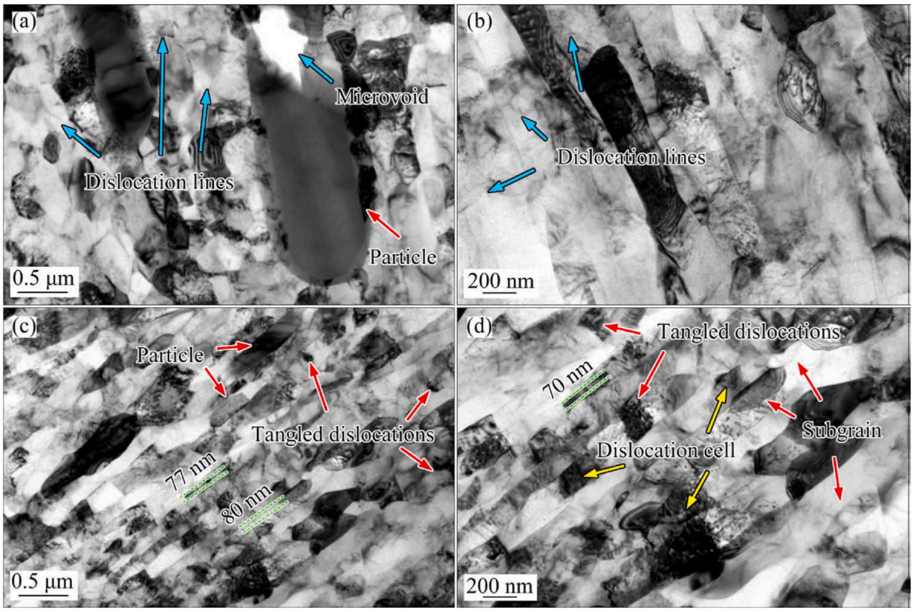

Fig. 12. TEM images of 3 wt% HEA-particles reinforced AMCs with 95% rolling reduction via AR (a, b) and ACR (c, d) processes [73]. Culled with permission from Elsevier.

conventional metal alloys, and pure metals [30,50]. A good number of authors have already studied the structural characteristics and mechanical properties of HEA particles reinforced AMCs produced by the powder metallurgy process [37,47,79–81].

Ogunbiyi et al. [79] reported the structural characteristics of $Fe_{1.2}CrZnCuAlTi_{0.8}$ HEA-particles reinforced 7075 Al-matrix composites manufactured by the sintering process. The findings of the study revealed that the incorporation of HEA-particles reinforcement resulted in a significant balance of mechanical characteristics, including microhardness, tensile strength, ductility, elastic modulus, flexural strength, and impact strength. The improvement was as a result of the uniform dispersion of the HEA particles in the Al matrix alloys and the presence of the intermetallic phases. According to the results analysis, 11.7% wt.% HEA, 75.2 MPa sintering pressure, and 447.7 °*C* sintering temperature are the best process parameters for obtaining the optimum combination of tensile properties in the Fe$_{1.2}$CrZnCuAlTi$_{0.8}$ HEA-particles reinforced 7075 Al-matrix composites.

Wang et al. [80] studied the microstructure and mechanical behaviour of CuZrNiAlTiW HEA particles reinforced AMCs fabricated by the spark plasma sintering process. CuZrAlTiNiW HEA particles in varied proportions: 10, 20 and 30 vol %, represented as Al10, Al20, and Al30, respectively, were dispersed in the Al-matrix by spark plasma sintering process. It is observed that certain active radicals in HEA reinforcement interact with the Al-matrix during the sintering process, leading to the formation of certain intermetallic phases which constitute the diffusion layer at the HEA/matrix interface. Hardness of the AMCs is observed to increase with the volume fraction of the reinforcement. At 30 vol % reinforcement, the dislocation network greatly increased and the hardness attained a value of 331 HV, which is about 10 times that of the Al-matrix. The strength increased at the expense of ductility with the increase in the volume fraction of the reinforcement. For instance, at 10 vol % reinforcement, the Al10 composite exhibits a 7.6% degree of plasticity, with yield strength and fracture strength measuring 258 and 344 MPa, respectively. In contrast, the values obtained for the plasticity, yield and fracture strength for the Al-matrix is 15.11%, 39 MPa, and 98 MPa, respectively. The high strength of composites was mainly due to the precipitation strengthening of in-situ B2 and WAl12 intermetallic phases, dispersion strengthening of BCC-particles, interfaces of Al concentration gradient among different sintered phases, as well as the large lattice distortion.

Lu et al. [81] studied the mechanical properties of nano-crystalized (NC) CoNiFeCrAl$_{0.6}$Ti$_{0.4}$ HEA particles reinforced AMCs fabricated by hot pressing and extrusion process. The HEA particles with varied concentrations ranging from 0 to 30 wt % HEA particles were uniformly dispersed in the 2024Al-matrix. Fig. 13 depicts the microstructure of the HEA-particle/2024Al composite. The BSE image for 7.5 wt%HEA-particle/2024Al composite shows that the shell is made up of numerous small HEA particles, while the core is made up of comparatively greater HEA particles embedded in the Al-matrix (Fig. 13b and c).

The stress-strain curves for the HEA/2024Al-matrix composites and unreinforced 2024Al-matrix are shown in Fig. 14a. The 7.5 wt% HEA-particles/2024Al composite exhibited a good combination of strength and ductility; and has a yield strength of 419 ± 12 MPa, which is 112 MPa greater than the 2024Al-matrix. The good plasticity and high strength of 7.5 wt% HEA-particles/2024Al composites are linked to the yield-point phenomena involving the Lüders deformation mechanism. This regained work-hardening ability contributes to the high strength and good plasticity of 7.5HEA-2024Al composites. The morphology of the fractured surface of 7.5 wt% HEA-particles/2024Al composites is characterised by many dimples suggesting a ductile fracture mode and indicating that a rather good metallurgical bonding exists in the interfaces between the 2024Al and NC-HEAp. This is a very rear phenomenon in conventional AMCs where ceramic materials are used as reinforcement. As seen in Fig. 14b, the mechanical properties of similar Al-matrix composites reinforced by various ceramic particles in comparison with HEA-particles reinforcement indicate that HEA-particles exhibit superior properties and therefore are good choices for reinforcement in Al matrix composites.

In a similar study, Yuan et al. [47] assessed the structural and mechanical behaviour of CoCrFeMnNi HEA-particles reinforced 2024 Al-matrix composites produced using the spark plasma sintering process. It is observed that a inter-diffusion layer (ID) developed between the Al-matrix and the CoCrFeMnNi HEA particles during the sintering process, as shown in Fig. 15. The hardness of the AMCs produced is determined to be 131.2 HV represents about 63.7% increase compared to the value of 82.1 HV obtained for the Al-matrix. It was as a result of the coupled effect of the particle reinforcement and the presence of the ID layer, which reduces sintering defects, further increases the hardness of the composite. Also, during the SPS process, the atoms diffuse uniformly in the diffusion layer leading to the formation of a gradient interface microstructure which was beneficial to reducing the stress concentration at the interface, and improve the stress distribution state and the bearing capacity of the composite. Finally, the formation of intermetallic phases at the diffusion layer obstructs dislocation motion, plugging the dislocations and increasing the resistance to deformation.

Chen et al. [37] studied the structural properties and mechanical behaviour of 7.5 vol % CoNiFeAl0.4Ti0.6Cr0.5 HEA particles reinforced 6061 Al-matrix composites produced by hot powder pressing and extrusion process. Three samples designated 6061 Al-HEAp-10h, 6061 Al-HEAp-20h, and 6061 Al-HEAp-40h were produced with milling time set to 10 h, 20 h, and 40 h, respectively. Fig. 16 shows the microstructure of 6061Al and HEA/6061Al composites at varied milling times. The microstructure of 6061 Al-HEAp-10h composites show a greater degree of homogeneous dispersion of the HEA-particles in the Al-matrix compared to those of 6061 Al-HEAp-20h 6061 and Al-HEAp-40h composites. The 6061Al-HEA-40h composite has a pronounced heterogeneous grain structure due to their associated recrystallisation behaviour and tiny HEA particle clusters. The ultimate tensile strength and fracture strain of the 6061Al-HEA-10h composite is 378 MPa and 8.4%, respectively. The composite of 6061Al-HEA-40 h demonstrated the highest ultimate strength and yield strength, estimating 385 and 348 MPa, respectively. Additionally, the fracture strain of this composite was found to be similar to that of the 6061Al-HEA-20h composite, which can be attributed to the formation of tiny clusters of HEA particles and a

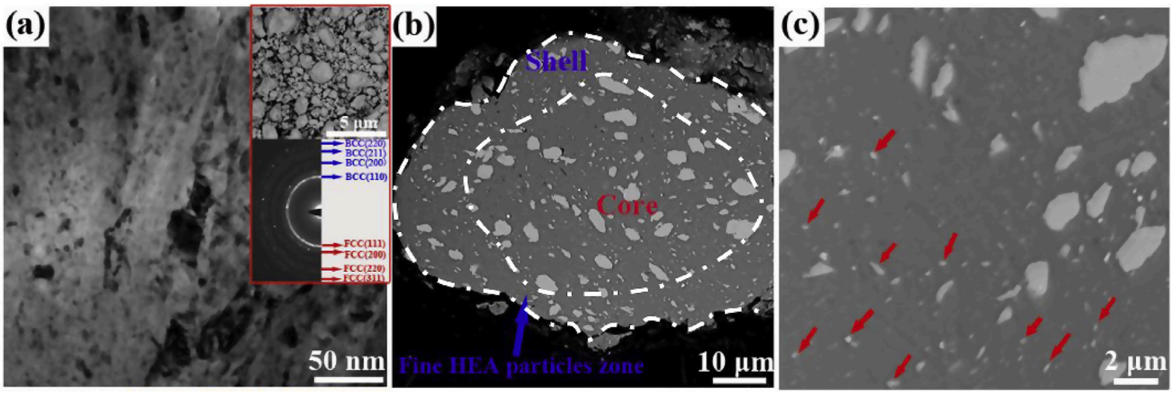

Fig. 13. Characteristics of the CoNiFeCrAl0.6Ti0.4 HEA powders and the composite: (a) bright-field TEM image of the 60 h milled CoNiFeCrAl0.6Ti0.4 HEA powder, (b) and (c) BSE images of the 15 h milled 7.5HEA-2024Al composite powder [81]. Culled with permission from Elsevier.

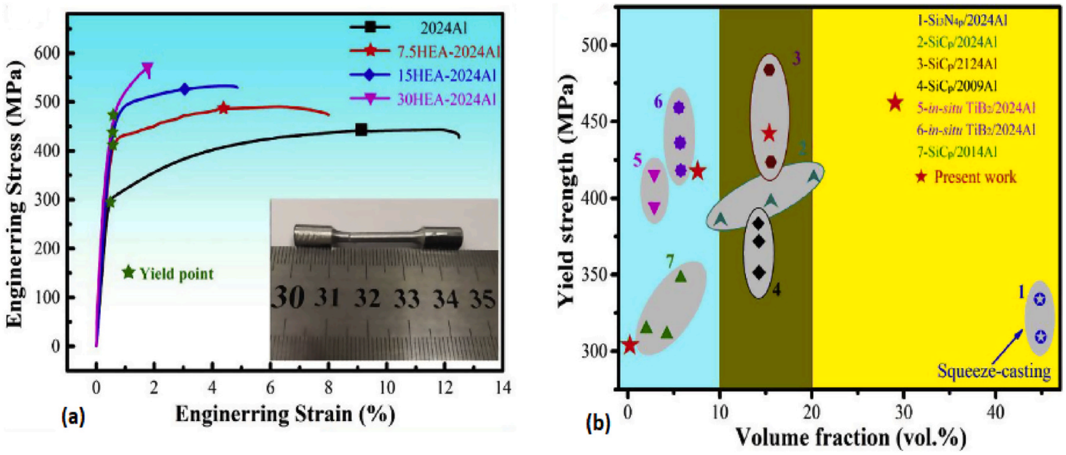

Fig. 14. Tensile properties of 2020 Al-matrix/HEA particles composites (a) stress-strain curves (b) properties of 2024Al-matrix reinforced with various materials in relation to HEA particles [81]. Culled with permission from Elsevier.

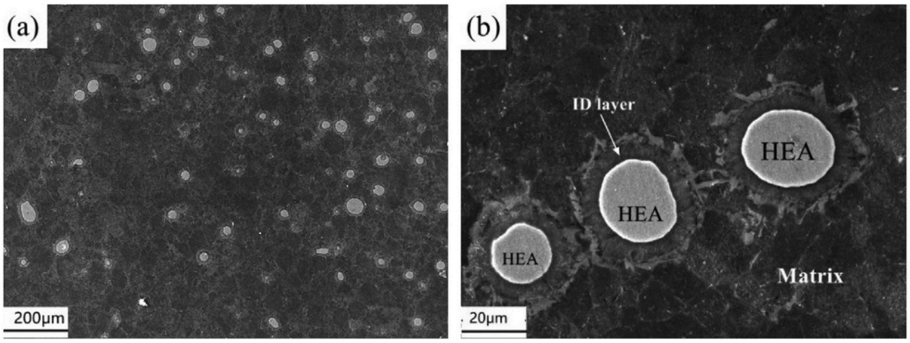

Fig. 15. Microstructure of CoCrFeMnNi HEA-particles reinforced 2024 Al-matrix composites showing SEM images at (a) low magnification; (b) high magnification [47]. Culled with permission from Elsevier.

heterogeneous grain structure. The enhanced mechanical properties of composites mostly arise from many mechanisms, including the Hall-Petch effect, load transfer, orowan strengthening, and geometrically necessary dislocations. The results presented in Fig. 17 have confirmed that processing parameters have a serious impact on the properties of AMCs reinforced with HEAs. Strength and hardness tend to increase with milling time.

Bin et al. [82] developed a novel high-entropy AlFeCrCoNi2.1 alloy particle Al matrix composite via selective laser melting and examined the effect on the mechanical properties. The average grain size of the HEA/AMC dropped from 4.17 to 3.24 μm when compared to the AlSi10Mg alloy. Furthermore, the width of the inner cell of the HEA/AMC was reduced to a value less than 0.3 μm. The HEA/AMC demonstrated superior mechanical properties compared to the AlSi10Mg sample, exhibiting higher tensile strength (478 MPa), compressive strength (719 MPa), tensile elongation (5.4%), and Vickers hardness (173 HV0.5). The observed improvement can be attributed to three factors. Firstly, the HEA particles acted as nucleating agents, slowing down the growth of cells by pinning the Si phase. Secondly, the alloying elements introduced by the dissolved HEA particles in the Al crystal lattice increased the distortion of Al, thus impeding the movement of dislocations. Lastly, unmelted HEA microparticles and newly precipitated spherical HEA nanoparticles in the Al matrix interacted with dislocations, hindering their motion. Therefore, the improvement in the mechanical properties was due to the effect of the refinement strengthening, solid-solution strengthening, and multiscale particle strengthening.

This result is in accordance with the observations of Maneesh et al. [83], Prakash et al. [84], and Prabakaran et al. [85], where powder metallurgy processing is used to fabricate HEA/Al-matrix composites. It can be deduced from these studies that sintering temperature and time, and milling time are among the important factors that determine the microstructure and mechanical behaviour of the formed composites. It can be concluded from the various literatures reviewed that HEA-particles exhibit superior mechanical and chemical properties as reinforcements in AMCs when compared to metallic glass, ceramics and conventional metal alloys.

3.3. *Friction stir processing technique*

Researchers have used innovative fabrication techniques to improve the compatibility between the HEA-particles reinforcements and the Al-matrix. These initiatives have improved their functional qualities and increased the strength-to-ductility ratio, which will better serve and broaden their range of service applications.

Li et al. [40] studied the mechanical properties of $Al_{0.8}$CoCrFeNi HEA particles reinforced AA5083 matrix composite fabricated using the friction stir manufacturing approach. The mechanical properties of the Al-matrix were improved by the inclusion of HEA particles. The produced AMCs have yield and ultimate tensile strengths of 200 MPa and 371 MPa, respectively, which are increases of 42% and 22% over the Al-matrix. The hardness of the composites is observed to increase with the increase in the volume fraction of the reinforcement. The great dimples observed at the fracture surface of the Al-matrix/Al0.8CoCrFeNi HEA-particles reinforced composites show a typical ductile fracture mode.

Yang et al. [39] studied the mechanical behaviour of 10 vol% AlCoCrFeNi HEA-particles reinforced 5083Al-matrix composites

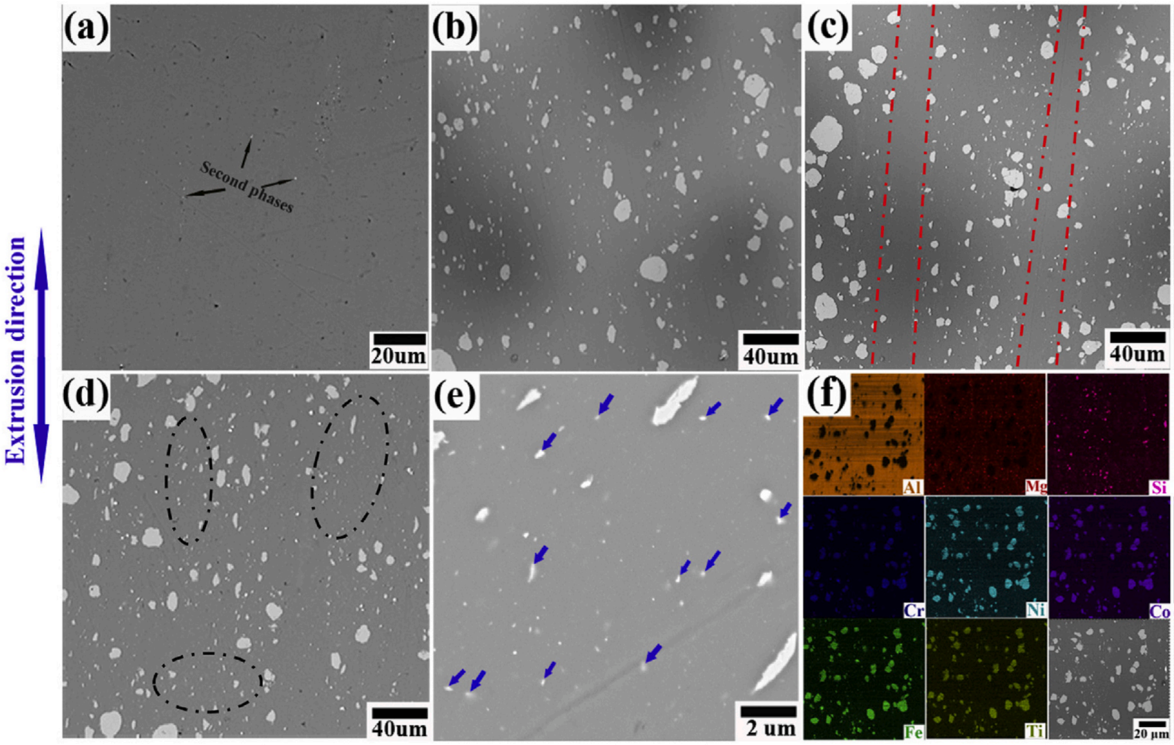

Fig. 16. Microstructure of 6061Al and HEA/6061Al composites (a) unreinforced 6061Al, (b) 6061Al-HEA-10 h composite, (c) 6061Al-HEA-20 h composite, (d) and (e) 6061Al-HEA-40 h composite, (f) EDS live mapping of the 6061Al-HEA-10 h composite [37]. Culled with permission from Elsevier.

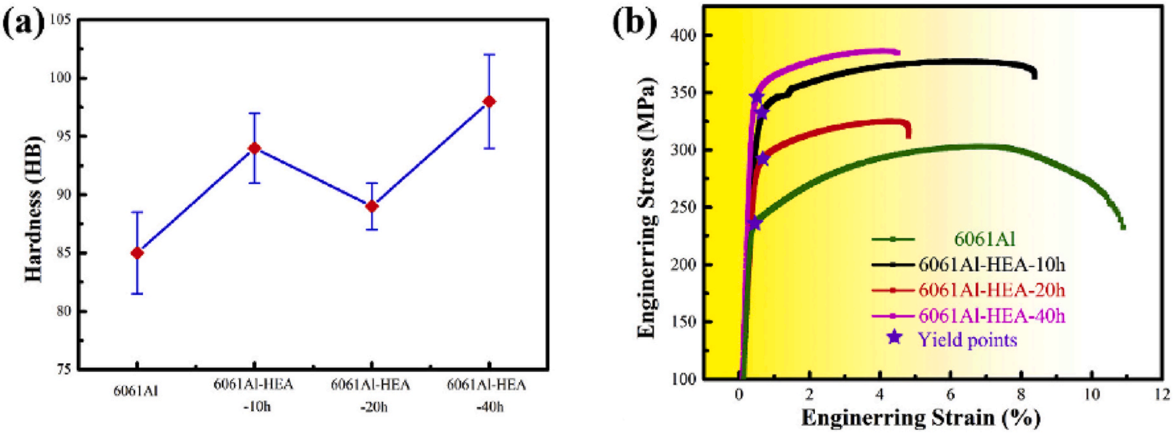

Fig. 17. The effect of milling time on the (a) hardness and (b) yield strength of the HEA/6061Al composites [37]. Culled with permission from Elsevier.

manufactured by submerged friction stir processing (SFSP) method. The study compares the tensile properties of commercial 5083Al plate is designated as base materials (BM), submerged friction stir processed 5083Al alloy designated as SFSPed 5083Al, and submerged friction stir processed HEA/5083Al composites is designated as SFSPed HEA/5083Al composites. Fig. 18 shows the tensile properties of the BM, SFSPed 5083Al, and SFSPed HEA/5083Al composites. Compared to the BM samples, the SFSPed HEA/5083Al composites demonstrated a 25.1% increase in yield strength and a 31.9% increase in ultimate tensile strength with a reasonable ductility of 18.9%. It was explained that the addition of HEA particles promotes dynamic recrystallisation by particle-stimulated nucleation mechanism leading to the observed improvement in their tensile properties.

In another study, Li et al. [86] studied the mechanical behaviour of $AlCoCrFeNi_{2.1}$ HEA particles reinforced AMCs produced by friction stir processing technique. As the weight percentage of the reinforcing HEA-particles increased, the strength and hardness of the composites increased concomitantly. The composites containing 15 wt% HEA-particles exhibited a 28.6% and 25.6% increase in hardness and tensile strength, respectively, reaching 72 HV and 222.9 MPa compared to the Al-matrix. The strengthening effect observed in HEA-particles/Al-matrix composites occurs by Hall-Petch and thermal mismatch strengthening mechanisms.

Recently, deep cryogenic treatment (DCT) has been employed to further improve Al/HEAp composites plasticity and their processing performance. The impact of deep cryogenic treatment on the mechanical properties and microstructural development of Al/FeCoNi1.5CrCu HEA-particles reinforced composites was studied by Liu et al. [87]. The results demonstrated that the internal tension produced during deep cryogenic treatment caused the (111) and (200) crystal face indices to change to (220). This suggests that deep cryogenic treatment has a strong effect on the plasticity of the AMCs. Based on the compression test results, the

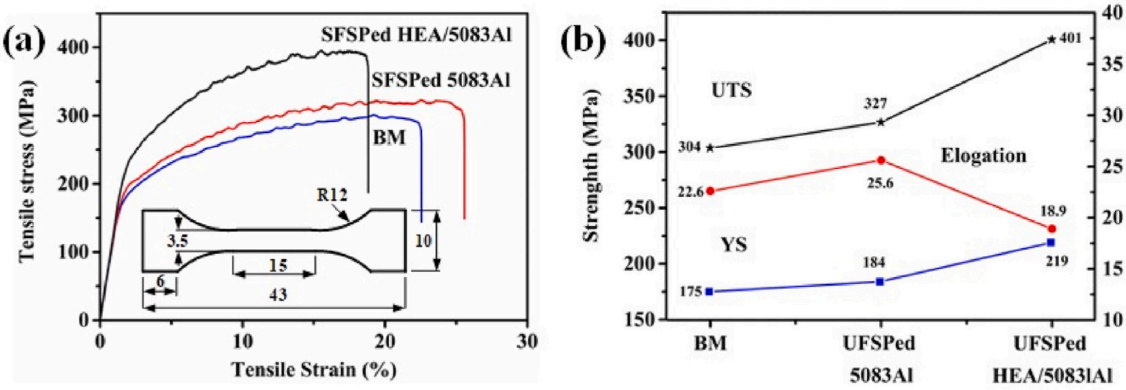

Fig. 18. Tensile properties of the BM, SFSPed 5083Al, and SFSPed HEA/5083Al composites: (a) stress-strain curves, (b) the variations in ductility versus strength [39]. Culled with permission from Elsevier.

treated composite plasticity is 142% higher than that of the untreated sample, indicating a significant improvement. It was noted that the fractures transition from a one-way propagation mode to two-way propagation, and that the multi-system slip caused the fracture toughness property of the treated composite to improve by 155.6% when compared to the samples without cryogenic treatment.

In the study by Wang et al. [88], they examined modifications in microstructure and mechanical characteristics of the CrMnFeCoNi HEAp/Al composite with varying levels of reinforcement. The microstructure analysis showed a significant reduction in the average grain size of the composites, ranging from 70.5% to 81.8%, compared to the aluminium processed by RFE. Additionally, the composites exhibited the formation of multiple second phases, as depicted in Fig. 19. The ultimate tensile strength (UTS) of the composite containing 19.8 wt % of high entropy alloy (HEA) was 224.5 MPa, exhibiting a remarkable improvement of 150.8% compared to the aluminium alloy. Additionally, the composite maintained a satisfactory uniform elongation of 16.7%. The enhancement in mechanical characteristics was attributed to the grain refinement mechanism, Orowan strengthening, load transfer strengthening, and dislocation strengthening.

Dwivedi and Sharma [89] conducted a study on the fabrication and characterization of AlSi7Mg0.3–based composite reinforced with

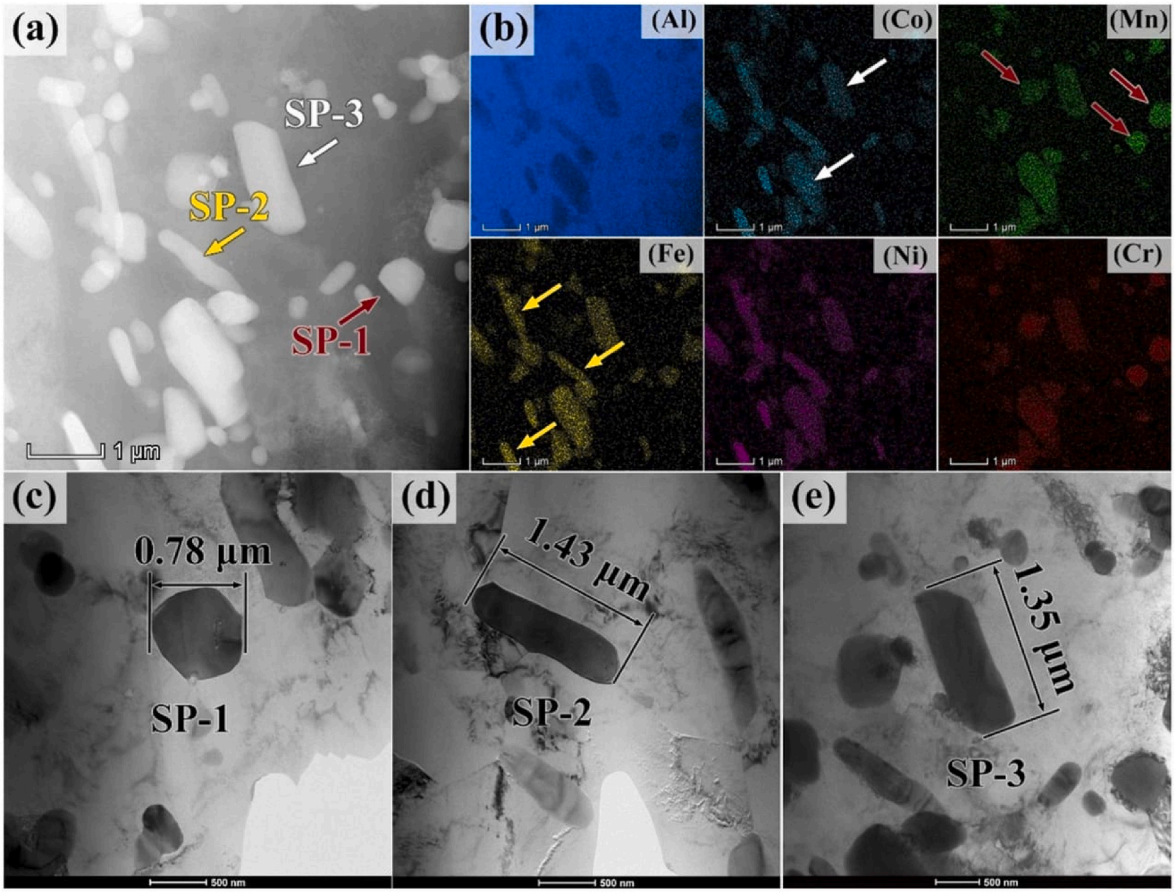

Fig. 19. TEM images and element mapping results of the sample S3: (a) the dark-field image of the TEM foil, (b) the corresponding element mapping results of (a), and (c–e) the magnification micrographs of the formed second phases [88]. Culled with permission from Elsevier.

AlCoCrFeNiCuSn HEAp. The addition of AlCoCrFeNiCuSn HEAp to aluminium matrix (AlSi7Mg0.3) using FSP technology greatly increased its tensile strength. The inclusion of AlCoCrFeNiCuSn HEA resulted in a significant enhancement of approximately 37.02% in the tensile strength of the aluminium alloy. This enhancement can be ascribed to many sources. Firstly, the even dispersion of HEAp within the aluminium matrix reduces the stress localization and facilitates the sharing of load between different phases, hence improving the overall mechanical strength. Furthermore, the robust continuous interfacial bonding between the HEAp and the aluminium matrix (AlSi7Mg0.3) facilitated effective transmission of stress. In addition, the microstructure was improved using FSP, resulting in a reduction of flaws and an enhancement of the material's mechanical characteristics. Together, these impacts led to a significant enhancement in the strength metrics of the composite. The incorporation of AlCoCrFeNiCuSn HEAp into the aluminium matrix using the FSP technology had a notable effect on the hardness property of the composite. The addition of HEAp resulted in a 52.45% increase in the hardness of the aluminium matrix. The intrinsic hardness of the HEAp, along with its even dispersion throughout the aluminium matrix, resulted in a significant enhancement of the

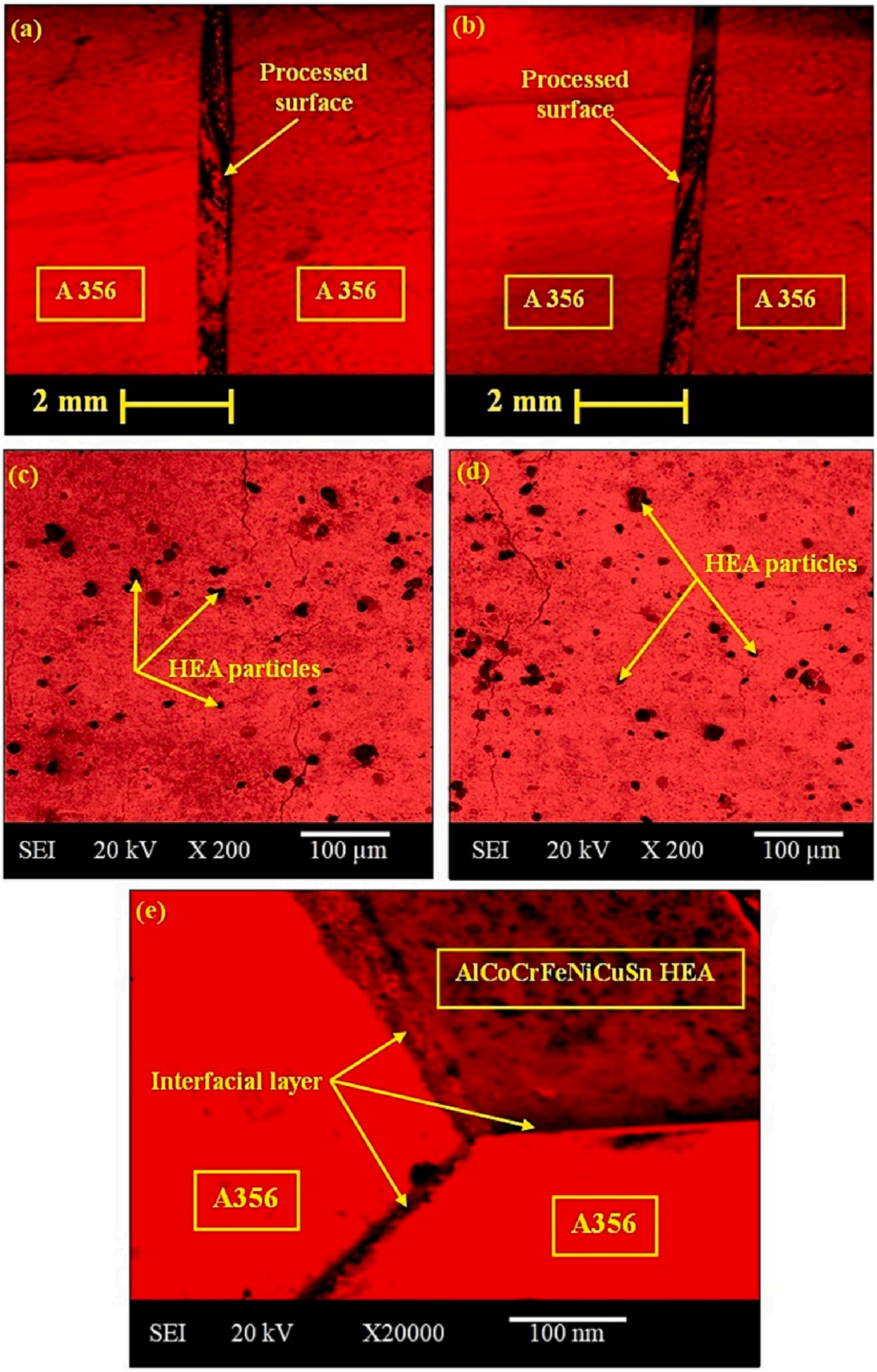

Fig. 20. AlSi7Mg0.3/AlCoCrFeNiCuSn HEA composite; (a & b) Macrostructure (c & d)) Microstructure, (d) Interfacial layer [89]. Culled with permission from Elsevier.

composite material's overall hardness. This improvement can be attributed to the robust interfacial adhesion and well-developed microstructure achieved using FSP (see Fig. 20).

The studies that have been evaluated indicate that the Al/HEAp composites have a notable improvement in yield strength, elongation, hardness property, and UTS. Grain refinement was enhanced by the friction stir processing method, which was evident in the increase in yield strength, hardness, and UTS. Composites produced by submerged friction stir processing techniques had superior mechanical properties compared to the composite samples of similar composition fabricated by friction stir processing method. The microstructural characteristics of HEA particles reinforced AMCs, which are fabricated using powder metallurgy, differ in terms of the chemistry and morphology of the diffusion layer formed at the Al/HEAp interface. These differences have a notable influence on the functional properties of the reinforced AMCs when compared to those produced through the casting process. AMCs reinforced with HEA particles, produced using additive manufacturing, demonstrate enhanced functional properties in comparison to AMCs created using traditional liquid and powder metallurgical methods. While the friction stir manufacturing method is effective in generating a strong bond between Al and HEAp at the interface, additive manufacturing techniques have been found to result in a faster solidification process, increase the uniformity of the microstructure, and enhance the characteristics of AMCs. Heat treatment processes such as DCT is noted to further improve the strength-to-ductile ratio of AMCs reinforced with HEA-particles. The works available in the literature were mostly based on tensile properties. To expand the applicability of these HEA-particles/Al-matrix composites, attention is required in the area of their damping properties, corrosion and tribological behaviour, weldability, and hot deformability, among other functional properties. Studies on how to optimise the processing parameters of the various fabrication methods is expected to attract research interest in the future. It is also important to note that the majority of the articles reviewed only compared their results with monolithic alloys; and little information is available regarding the impact of hybrid reinforcement on the overall mechanical properties of AMCs. Table 2 compares the mechanical properties derived from AMCs reinforced with HEA particles and traditional ceramic reinforcements. It is observed that HEA particles reinforced AMCs have superior properties in terms of strength and ductility when compared to their counterparts reinforced with B_4C, SiC, Al_2O_3 and agro-waste derived ceramic materials. However, the cost of HEAs and their higher density compared with conventional ceramics reinforcements remain a major drawback in their utilization. The use of hybrid reinforcement (HEAs and ceramics) can help to mitigate this challenge.

Table 2
The mechanical properties derived from AMCs reinforced with HEA particles versus AMCs reinforced with traditional ceramic materials.

Properties of AMCs reinforced with HEA-particles		Properties of AMCs reinforced with ceramic materials	
Composites	Mechanical properties	Composites	Mechanical properties
1060 Al/19.8 wt% CrMnFeCoNi	Wang et al. [88] UTS = 224.5 MPa Elongation = 16.7%	Al 6063/12 wt% (Palm kernel ash (PKA) + SiC)	Ikele et al. [90] UTS = 159.08 MPa Elongation = 8.58%
6061 Al/10 vol% $AlFeNiCrCoTi_{0.5}$	Huan et al. [64] UTS = 188 MPa Elongation = 13.5%	Al/8 wt% SiC	Alaneme et al. [91] UTS = 130.5 MPa Elongation = 9.5%
5083 Al/$Al_{0.8}CoCrFeNi$	Li et al. [40] UTS = 371 MPa Elongation = 18.8%	5083 Al/10 wt% SiC	Karabulut et al. [92] UTS = 134 MPa, Elongation = 8.6%
5083 Al/10 vol% AlCoCrFeNi	Yang et al. [39] UTS = 401 MPa Elongation = 18.9%	356Al/3 vol% nano-TiB_2	Akbari et al. [93] UTS = 283 MPa, Elongation = 2%
6061-T6 Al/15 wt%. AlCoCrFeNi HEA	Li et al. [86] UTS = 222.9 MPa Elongation = 19.3%	A356 Al/Cr–SiC	Mousavian et al. [94] UTS = 175 MPa Elongation = 5.3%
5083 Al/AlCoCrFeNi	Yang et al. [39] UTS = 327 MPa Elongation = 25.6%	A356 Al/Cu–SiC	Mousavian et al. [94] UTS = 168 MPa Elongation = 6.7%
Al6061+1HEA+3B_4C	Chitturi et al. [49] UTS = 100.69 MPa Elongation = 17.89%	Al 6063/10 wt% (Palm kernel ash (PKA) + SiC)	Ikele et al. [90] UTS = 142.71 MPa Elongation = 7.58%
Al6061+3HEA+1B_4C	Chitturi et al. [49] UTS = 125.19 MPa Elongation = 22.88%	Al/Corn Cob Ash and SiC	Fatile et al. [95] UTS = 142.71 MPa Elongation = 7.58%
Al/CuZrNiAlTiW	Wang et al. [80] UTS = 344 MPa Elongation = 7.23%	Al/Rice Hush Ash (RSA), Cu and Mg	Muni et al. [96] UTS = 95.3 MPa Elongation = 7.75%
Al/CuZrNiAlTiW	Wang et al. [80] UTS = 544 MPa Elongation = 6.67%	Al/Bamboo leaf Ash and SiC	Alaneme et al. [97] UTS = 150 MPa Elongation = 18%
7075Al/3 wt % AlCrTiV	Huang et al. [63] UTS = 89.2 MPa Elongation = 46.8%	Al-3wt% Al_2O_3	Chandru &Vishnu [98] UTS = 114 MPa Elongation = 1%
7075Al/6 wt % AlCrTiV	Huang et al. [63] UTS = 104.7 MPa Elongation = 18.7%	Al-4wt% Al_2O_3	Chandru &Vishnu [98] UTS = 169 MPa Elongation = 0.5%

3.4. *Wear behaviour of aluminium based composites reinforced with HEAp*

AMCs have superior wear resistance than normal Al alloys, enabling them to handle harsh braking demands. However, their weak fracture toughness and low ductility impeded their use in service applications. HEAs show outstanding physical properties, such as great strength metrics and hardness, good thermal stability, and high degrees of wear resistance. HEAp have received great interest as unique multi-principal element metal alloys because of their outstanding wear resistance, which makes them a potential material that can serve as a suitable reinforcement in Al-based composites [99,100]. In recent research, Verma and Singh [101] employed a novel HEAp (CoMoMnNiV) as a reinforcement phase on the Al7075 matrix by stir-squeeze casting process. The evaluation of wear result during dry sliding demonstrated that the Al/HEAp composites have the capacity to endure a greater load in comparison to the unreinforced alloy, and exhibit superior resistance to wear. There was a notable decrease in the rate at which wear occurred for all levels of HEA content. However, the composites that contained 8 wt% HEAp exhibited the greatest wear resistance. The increased wear resistance seen in the Al reinforced with HEAp was related to the presence of hard HEA particles, the even dispersion of the HEA particles in the aluminium matrix, the continuous strong bonding at the interface between the HEAp and the Al matrix, and the enhanced strength attained by the composites. The presence of smaller grain sizes in the composites' microstructure impedes the movement of dislocations and decreases the likelihood of crack propagation, leading to enhanced hardness and superior resistance to wear. Additionally, the uniform dispersion resulted in a microstructure encompassing numerous resilient phases, consequently impeding the development of wear spots and diminishing friction. Fig. 21 presents a comparison of the worn surfaces of the unreinforced Al alloy and the Al/HEAp composite. Comparatively, the surface of the AA7075/6 wt% HEAp composite displayed a smoother texture and showed little signs of wear debris, indicating its superiority over the unreinforced alloy.

As pioneers in the study of the tribological behaviour of HEAp/AMCs, Zhang et al. [102] investigated the wear behaviour of varying fractions of Al0.5CoCrFeNi HEAp reinforcement on the AA2219 aluminium matrix sheets fabricated through the mechanical stirring casting process. It was found from the wear test analysis that the hard HEAp prevented the contact surface from plastically deforming, which increased the AMCs' wear resistance. The AMC exhibited a significantly enhanced ability to withstand crack initiation, propagation, and fracture along the interface, and this is linked to its excellent interfacial bonding between the matrix and the reinforcement as well as the HEAp-dislocations interaction. The composites' wear track under a 30 kN load is depicted in Fig. 22. Similarly, in the research by Prakash et al. [84], AlCoCrCuFe HEAp greatly enhanced the wear resistance of the Al/HEAp composites. As the addition of HEAp reinforcement increased, the wear rate of the Al-based composite fell dramatically.

Bin et al. [82] investigated the wear characteristics of AlSi10Mg alloy reinforced with AlFeCrCoNi2.1 high entropy alloy particles. The coefficient of friction (COF) of the AlSi10Mg sample exhibited significant fluctuations initially, followed by a progressive decrease to a low value during the early stages of the friction process, and subsequently remained stable. The wear reduction performance of the AlSi10Mg sample was enhanced as a result of the abundant occurrence of thin Si phases. The COF of the composite was approximately 0.05 lower compared to the AlSi10Mg sample. Upon the incorporation of HEA particles, the breadth of wear scars diminished to 493 μm. The worn surface of the composite material exhibited clean grooves, delaminated pits, and a limited amount of micro-debris. Plastic deformation was seen at the borders of the wear scar, however its severity was notably decreased compared to that of the AlSi10Mg alloy. The addition of HEA particles greatly enhanced the wear resistance of the AlSi10Mg alloy because of the strong interfacial bonding between the HEA particles and the Al matrix.

The manufacturing approach has been applied to improve the wear resistance of Al/HEAp composites further. Yang et al. [103] conducted a wear test on AlCoCrFeNi HEAp-reinforced A5083 AMCs manufactured using underwater friction stir processing (UFSP). The Al/HEAp composites exhibited the lowest coefficient of friction and wear rate across all the test specimens. Furthermore, the wear rate of the composites fell by 48.6% compared to the monolithic Al matrix, as shown in Fig. 23. The inclusion of HEAp and refined intermetallic compounds Al6(Mn, Fe) hindered the movement of dislocations, therefore preventing the formation as well as the propagation of micro-cracks. Furthermore, the utilization of UFSP greatly diminished the likelihood of interfacial reactions, hence enhancing the metallurgical bonds between the reinforcements and the matrix.

Li et al. [7] revealed that the wear resistance of the generated AMCs enhanced owing to the hard Al3Ti and Al–Ti–Cr phases present in the matrix of the Al–Fe–Ni–Cr–Co–Ti HEAp-reinforced Al-based composites. In a related investigation, Gao et al. [50] examined the effects of the number of processing passes and the amount of reinforcing particles on the wear properties of friction stir process manufactured FeCoNiCrAl HEAp-reinforced 5083 Al-based composites. When compared to the 5083-Al base alloy and friction stir-treated samples without the Fe–Co–Ni–Cr–Al HEAp, the Al/HEAp composites demonstrated higher micro-hardness and wear resistance.

Dwivedi and Sharma [89] conducted a study on the fabrication and characterization of AlSi7Mg0.3–based composite reinforced with AlCoCrFeNiCuSn HEAp. It was reported that the addition of AlCoCrFeNiCuSn HEAp to the aluminium matrix (AlSi7Mg0.3) using the FSP technology resulted in a significant enhancement in the composite's ability to resist wear. The unreinforced alloy exhibited a wear rate of 0.0043 mm^3/m. The wear rate of the AlSi7Mg0.3/HEAp composite was determined to be 0.0024 mm^3/m. It was reported that the observed enhanced wear resistance was as a result of the remarkable hardness properties of the HEAp, resulting in a reduced vulnerability of the material to abrasion, wear, and damage caused by friction. The robust continuous interfacial adhesion and homogeneous dispersion of HEAp inside the matrix additionally contributed to the enhancement of wear resistance. The surface morphology of AlSi7Mg0.3, which has been modified by introducing AlCoCrFeNiCuSn HEA through FSP, exhibits clear features such as cleavage facets, sliding direction patterns, and grooves (Fig. 24). These features indicated a mixture of adhesive and abrasive wear mechanisms, which demonstrate how the material reacts to mechanical stresses and frictional forces during use.

A number of the most current experiments on Al/HEAp-reinforced composites were reviewed in this study. When compared to Al alloys, the wear resistance and friction coefficient of composites are often improved by HEAp reinforcing. Intermetallic compounds also have a big influence on composite wear resistance. Based on the comprehensive analysis of the studies examined in this section, it can be concluded that augmenting the volume fraction of the high-entropy alloy (HEA) particle yields a noteworthy enhancement in the wear resistance of the resultant composites. However, the majority of experiments conducted have been restricted to a weight percentage fraction of 8 wt % for HEAp and have demonstrated the maximum level of resistance to wear. Furthermore, it was observed that all compositions of HEA exhibited a notable enhancement in terms of wear resistance. Further research on the wear characteristics of Al/HEAp composites is, nonetheless, required. This research should concentrate on examining the impacts of various HEAp

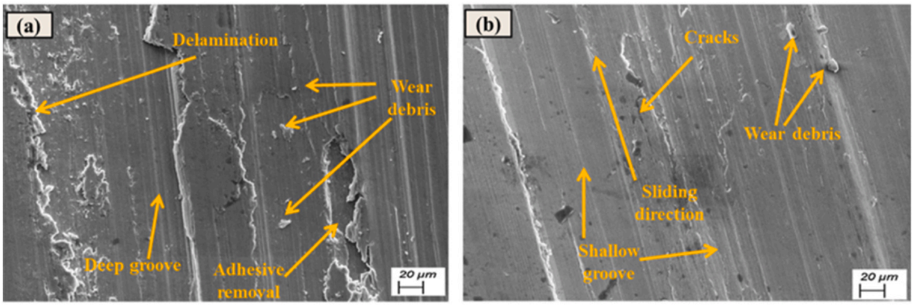

Fig. 21. SEM morphology of worn-out surfaces of (a) AA7075 alloy, (b) HEAp composite [101]. Culled with permission from Elsevier.

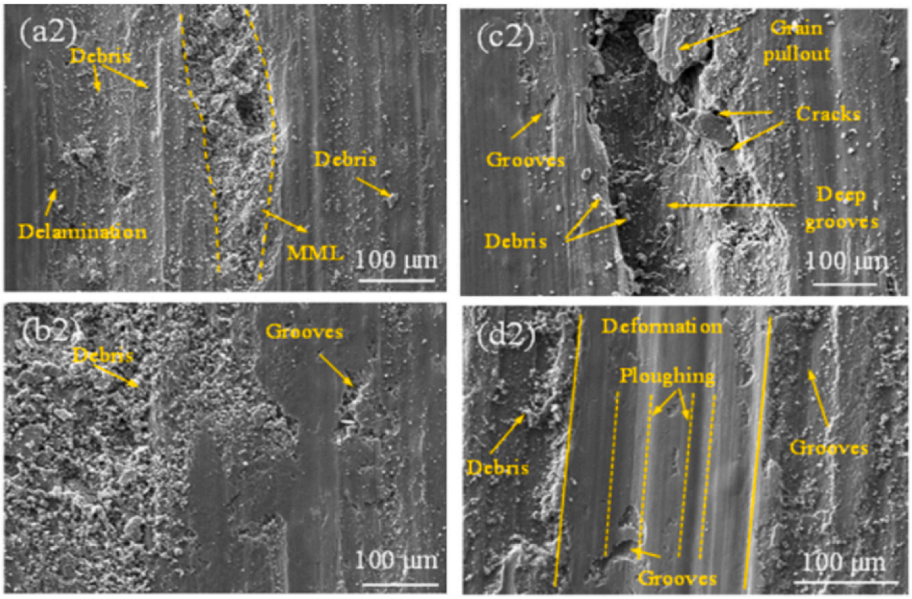

Fig. 22. Wear track topography for the different HEAp at a fixed applied load of 30 kN and sliding velocity of 70 mm/s for (a2) AA2219, (b2) 1.5 wt%, (c2) 3.0 wt% and (d2) 5.0 wt% high entropy alloy particle/Al matrix composites (MML – mechanically mixed layer) [102] culled with permission from Elsevier.

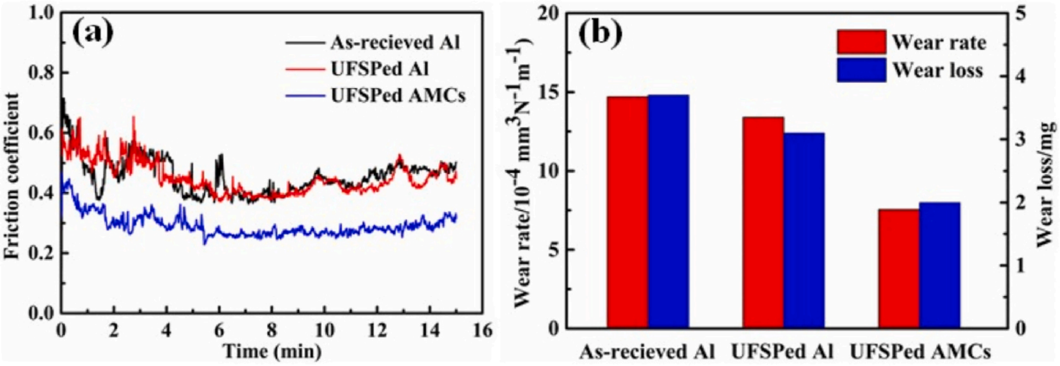

Fig. 23. Comparison of (a) the friction coefficient and (b) the wear rate and weight loss of the as-received Al, UFSPed Al and UFSPed AMCs [103]. Culled with permission from Elsevier.

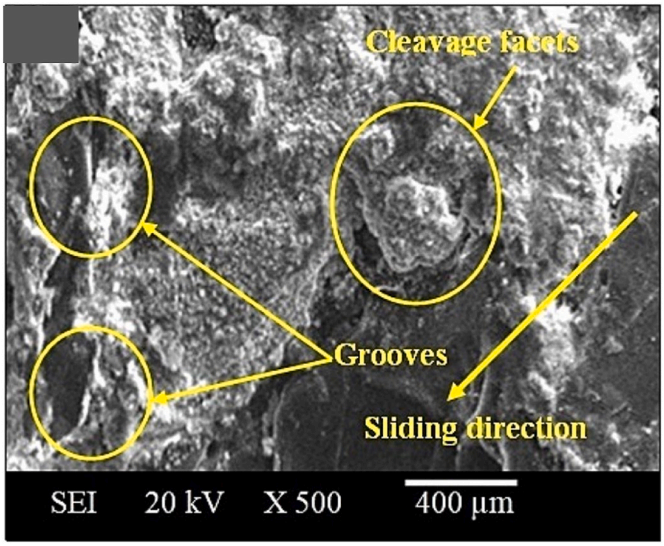

Fig. 24. Wear tracks of the AlSi7Mg0.3/HEAp composite [89]. Culled with permission from Elsevier.

reinforcement, hybrid AMCs, processing methods, and heat treatment procedures on the wear behaviour of these novel composites.

Table 3 presents a comparison of the wear qualities obtained from AMCs that are reinforced with HEA particles and those reinforced with standard ceramic materials. The wear properties of HEA particles on AMCs were found to be superior in terms of coefficient of friction (COF) and wear rate compared to AMCs reinforced with B4C, SiC, Al_2O_3, ilmenite, and porcelain ceramic materials. Nevertheless, the expense of HEAs and their greater density compared to traditional ceramic reinforcements continue to be a significant limitation in their application. Utilising hybrid reinforcement, which combines high-entropy alloys (HEAs) and ceramics, can effectively address this difficulty. Nevertheless, future research must prioritise the comparison of wear rate and wear mechanism between typical aluminum-based composites with ceramic reinforcement and aluminum/high-entropy alloy (Al/HEAp). To enhance the wear resistance of composites, it is imperative to consider this comparison in forthcoming research endeavours.

4. Corrosion resistance of aluminium based composites reinforced with HEAp

Evaluation of research on the corrosion resistance of Al-based composites reinforced with HEAp revealed that, in comparison to their alloy

Table 3

Comparison of the wear properties of the AMCs reinforced with HEA particles versus AMCs reinforced with traditional ceramic materials.

AMCs reinforced with HEA-particles		AMCs reinforced with Ceramics-particles	
Composites	Wear Properties	Composite	Wear Properties
AA2219/0.5 wt% $Al_{0.5}CoCrFeNi$	Zhang et al. [102] COF - 0.45 X 10^{-3} Wear rate – 0.32 mm^3/Nm	AlSi10Mg/2 wt% SiC	Xi et al. [104] COF - 0.12 Wear rate – 1.84 × 10^{-3} mm^3/Nm
AA2219/3 wt % $Al_{0.5}CoCrFeNi$	Zhang et al. [102] COF - 0.47 X 10^{-3} Wear rate – 0.4 mm^3/Nm	AlSi10Mg/3 wt% SiC	Xi et al. [104] COF - 0.16 Wear rate – 2.08 × 10^{-3} mm^3/Nm
AA5083/AlCoCrFeNi	Yang et al. [103] COF - 0.292 Wear rate – 7.55 × 10^{-4} mm^3/Nm	AA7075/4 wt%B_4C/12 wt% Porcelain	Aherwar et al. [105] COF – 0.072
5083/$Al_{0.8}FeCoNiCrCu_{0.5}$	Li & Shi [106] Wear rate – 1.19 × 10^{-5} mm^3/Nm	LM13-Al/10 wt%B_4C	Gupta et al. [107] COF - 0.75 Wear rate – 5.5 × 10^{-2} mm^3/Nm
5083/$Al_{0.8}FeCoNiCrCu_{0.5}Si_{0.5}$	Li & Shi [106] Wear rate – 8.99 × 10^{-7} mm^3/Nm	AA7075/5 wt % Al_2O_3	Al-Salihi et al. [108] Wear rate – 5.61 × 10^{-2} mm^3/Nm
Al/4 wt % AlFeNiCrCoTi	Li et al. [7] COF – 0.36 Wear rate – 1.92 × 10^{-9} mm^3/Nm	AA7075/3 wt % Al_2O_3	Al-Salihi et al. [108] Wear rate – 7.67 × 10^{-2} mm^3/Nm
Al/5 wt % AlFeNiCrCoTi	Li et al. [7] COF – 0.26 Wear rate – 1.125 × 10^{-9} mm^3/Nm	LM13-Al/15 wt% B_4C	Gupta et al. [107] COF – 0.7 Wear rate – 5.2 × 10^{-2} mm^3/Nm
Al/6 wt % AlFeNiCrCoTi	Li et al. [7] COF – 0.24 Wear rate – 2.27 × 10^{-9} mm^3/Nm	LM13-Al/10 wt% ilmenite	Gupta et al. [107] COF - 0.68 Wear rate – 4.0 × 10^{-2} mm^3/Nm

equivalents, AMCs' corrosion resistance was primarily increased by the use of HEAp as reinforcement. Nevertheless, compared to their unreinforced equivalents, the corrosion resistance of traditional ceramic-reinforced AMCs is lower [54]. The various approaches have also been investigated to demonstrate the distinct role that this processing pathway plays in the distinct corrosion potential that these composites exhibit. Ananisdis et al. [54] used powder metallurgy to create a unique AMC reinforced with MoTaNbVW refractory HEAp and evaluated how well it performed in a 3.5% NaCl solution in terms of corrosion. In a 3.5% NaCl solution, the resulting Al/HEAp composites and the unreinforced Al alloy were prone to localised types of corrosion. By stabilising the oxide coating, HEAp enhanced corrosion performance. It was also noted that when HEAp weight percentage rose, the amount of Al that was sensitive to deterioration decreased. On the other hand, HEAp cause discontinuities to appear on the Al oxide coating as the volume percentage of the reinforcement increases. These discontinuities might act as corrosion starting sites at the interface between the reinforcement and Al. The alloys' susceptibility to galvanic corrosion will rise with the HEAp, hastening the dissolution of Al on the Al/HEAp contact. Nonetheless, the galvanic impact is reduced by the reinforcement's uniform distribution and the absence of intermetallic phases at the contact. Therefore, it would seem that the corrosion of the matrix controls a significant portion of the sintered composites' corrosion resistance.

The corrosion resistance of Al-based composites reinforced with varying vol. % of CuZrNiAlTiW HEAp (10, 20 and 30 vol %, denoted as Al10, Al20, and Al30 in Fig. 24) produced by mechanical alloying and spark plasma sintering was assessed by Wang et al. [80]. The AMCs exhibited higher corrosion resistance due to the presence of Ni and W in the transition layer, strengthened the stability of the passivation-formed protective layer, the superior relative density and sintering quality of the AMCs, and the addition of HEAp strengthened Al's resistance to pitting corrosion. The Al10 composites exhibited the lower general corrosion rate, among the SPSed pure Al and other Al-HEA composites, further demonstrating the enhanced general corrosion resistance (see Fig. 25).

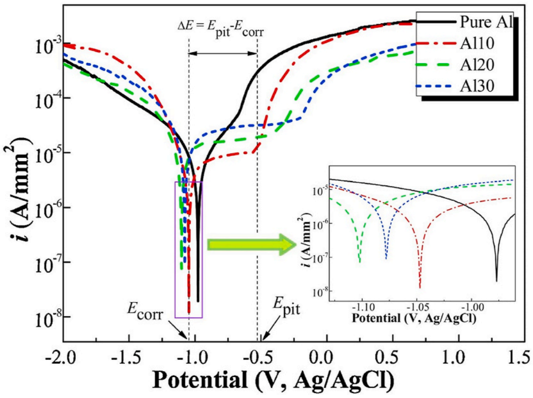

Fig. 25. Potentiodynamic polarization curves and local magnification for the SPS-ed pure Al, and Al-based composites [80]. Culled with permission from Elsevier.

In the combination of cold spray (CS) fabrication process and modification by FSP, Han et al. [109] examined the corrosion behaviour of high entropy alloy (CoCrFeNi) particles reinforced aluminium (6061) matrix composite at ambient temperature in a 3.5 wt% NaCl solution for immersion period of 12, 24 and 36 h. Over the span of 12–36 h, the rate at which the oxide film formed surpassed the rate of dissolution when the samples were immersed in a 3.5 wt% NaCl solution. The primary corrosion mechanism differed between CSed and FSPed samples, with particle dissolution occurring around micro-pores for CSed and pitting for FSPed samples. During the polarization process, FSPed samples demonstrated a reduced corrosion susceptibility and an elevated corrosion rate, attributed to their dense and uniform microstructure, low geometric necessary dislocation (GND) density, and the dispersion of high-entropy alloy (HEA) particles. More specifically, after 24 h of immersion time, both the CSed and FSPed samples demonstrated optimum resistance to micro-pores and pitting corrosion.

Dwivedi and Sharma [89] conducted a study on the fabrication and characterization of AlSi7Mg0.3–based composite reinforced with AlCoCrFeNiCuSn HEAp. The incorporation of AlCoCrFeNiCuSn HEAp into AlSi7Mg0.3 using the FSP technology greatly improves the composite's ability to resist corrosion. The HEA's natural resistance to corrosion, along with its even distribution throughout the matrix, forms a protective shield against corrosion damage. The robust continuous interfacial adhesion additionally hindered the penetration of corrosive elements. The surface morphology of the aluminium matrix, after the addition of AlCoCrFeNiCuSn HEA through FSP, showed isolated corrosion pits (Fig. 26). The presence of these pits signifies specific regions

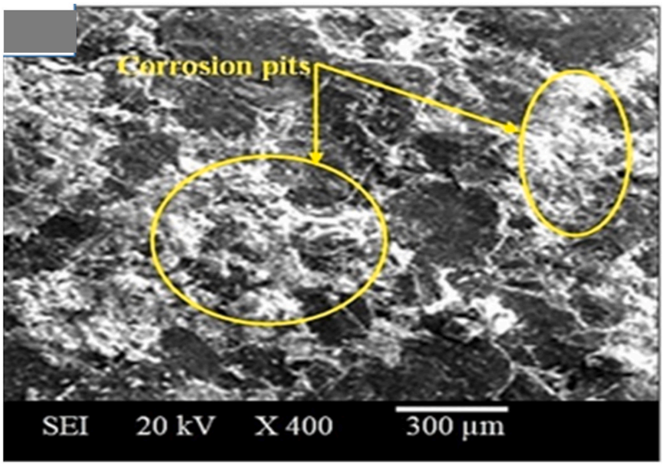

Fig. 26. SEM corroded surface of the AlSi7Mg0.3/HEAp composite [89]. Culled with permission from Elsevier.

where the material has deteriorated, emphasising the necessity for continuous safeguarding and mitigating strategies to uphold the composite's ability to resist corrosion in corrosive medium.

In summary, it is noteworthy that HEAp significantly affects the stability of the oxide film that passivation generates, serving as a barrier and reducing the rate at which the matrix structure corrodes. The composition and distinctive characteristics of the HEAp have a significant impact on this. The inclusion of particular elements, such as nickel (Ni) and tungsten (W), along with the even dispersion of high-entropy alloy (HEAp) and the lack of intermetallic phases, played a crucial role in enhancing the stability of the protective layer established through passivation. Consequently, this led to an improvement in the corrosion resistance of the composites produced. Moreover, the uniform dispersion of the high-entropy alloy (HEAp) inside the composite matrix is significantly influenced by various manufacturing methods. The findings demonstrate that the friction stir processsed composites exhibited a compact and consistent microstructure, facilitating the even distribution of high-entropy alloy (HEA) particles inside the matrix. Consequently, this leads to a notable decrease in their corrosion susceptibility. However, the authors of these researches did not compare the corrosion rates of Al/HEAp composites and traditional Al-based composites with ceramic reinforcements. Therefore, to produce composites with the best corrosion resistance, future research should take this comparison into account. Furthermore, there is dearth of publication in this area, intensive research is needed to clarify the underlying mechanisms for the corrosion behaviour of Al/HEAp composites.

5. Thermal stability of HEAp reinforced Al-matrix composites

HEA particles are widely regarded as a highly favourable choice for reinforcing alloy matrix composites (AMCs) due to their exceptional thermal stability and their favourable strength/ductility balance [69]. Only a few studies have looked into the thermal stability of HEAp-reinforced Al-matrix composites to determine their viability for use in high temperature applications. The microstructure and thermal stability of aluminium matrix composites reinforced with AlSiCrMnFeNiCu HEA were investigated by Shadangi et al. [110] using the powder metallurgy method. A differential thermal analysis thermogram was employed to assess the thermal stability, with a scan rate of 20 K/min. The experimental findings indicate that there were no observable alterations in the structure of the Al matrix, B2-type, and Cr5Si3-type phases in high-entropy alloy (HEA) at temperatures below 560 °C. This suggests that the HEAp reinforced Al-matrix composites were thermally stable until the Al-matrix melted at 650 °C. The composite's enhanced thermal stability is ascribed to the creation of a thin diffusion layer with a thickness ranging from 400 to 500 nm at the interface between the HEAp and the Al matrix. The composites' high thermal strength can be attributed to the intermetallic compounds that are produced at the HEAp/Al-matrix interface, which show good interfacial stability [47,111]. The mechanisms underlying the interfacial stabilisation between HEAp and the aluminium alloy matrix remain unclear, thereby necessitating further investigation in future research.

6. Comparative analysis for the choice of reinforcement

A comparative study of AMCs reinforced with various material systems was conducted, and a materials selection chart was developed to compare the performance of the reinforcements based on their strength-to-ductility ratio at room temperature. Utilising the yield strength, percentage elongation, and UTS data from supplemental Table X1, X2, and X3, a materials selection chart was constructed as shown in Fig. 27. Conventional metallic systems, hybrid systems, metallic glass and HEA reinforcements outperformed the conventional AMCs with ceramics reinforcements. Moreover, the hybrid reinforcements composed of conventional and agrowaste derived ceramics improved the performance of the ceramic reinforced AMCs, thereby, the agrowaste derived ceramics inclusion improved the mechanical properties of AMCs. Ranking the performance of these reinforcement, it was clearly observed that the HEA reinforcement stood out among all the reinforcement in terms of their strength/ductility balance. Then, followed by the metallic reinforcement, with relatively good strength/ductility balance. Next, the metallic glass reinforcement with high mechanical strength but relatively lower ductility compared to the conventional metallic systems. The metallic glass reinforcements were observed to have comparatively similar ductility range with ceramic reinforced AMC but high strength values showing that the metallic glass reinforcement does not address the main issue for the shift to metallic systems in addressing the poor ductility observed in ceramic reinforced AMC. Overall, the conventional ceramic reinforced AMC had the lowest performance. Therefore, based on the chart, it can be inferred that HEA reinforcements have significant potential and represent the optimal selection of reinforcing material for the design of AMCs characterized by their high-performance indices.

7. Challenges and further research directions

This paper evaluates the advancements achieved through the transition from traditional ceramic reinforcements in aluminium matrix composites (AMCs) to metallic-based reinforcements, particularly

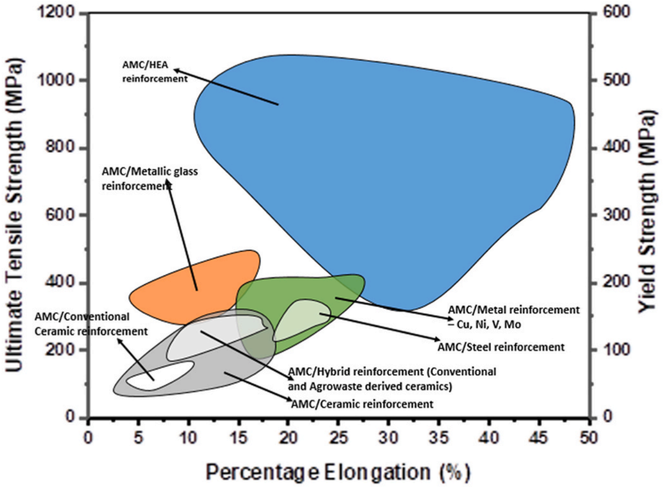

Fig. 27. Material selection chart for aluminium matrix composites (AMCs) with different reinforcement materials (conventional and agrowaste derived ceramics, metals, metallic glass, hybrid and high entropy alloys (HEAs)).

focusing on HEAs. Excellent wetting and robust continuous interface bonding between the matrix and HEAp reinforcement have been realised. Therefore, it can be observed that HEAp-reinforced AMCs exhibit enhanced mechanical and functional characteristics in comparison to their ceramic-reinforced counterparts, including B_4C, SiC, Al_2O_3 and agro-waste derived ceramic materials. However, it is noteworthy to state that the majority of the reviewed studies lack comprehensive comparisons with conventional AMCs where ceramic systems are used as reinforcements. It is imperative to address this gap for a thorough assessment of the progress made in terms of properties like ductility, fracture toughness, and other functional attributes when employing HEAs as reinforcements in AMCs. Furthermore, there is a need for additional research to comprehend the mechanisms of matrix-reinforcement interactions, especially with quaternary and more multi-component complex alloy systems serving as reinforcement. Also, little information is available regarding the impact of hybrid reinforcement on the overall mechanical properties of AMCs. These aspects remain an open and unexplored avenue for future investigations. The development of process technology aimed at controlling interface reactions between aluminium matrix and HEAp reinforcement to fabricate composites with enhanced functional characteristics is anticipated to be a focal point of research in the coming years. Another area expected to drive technological advancements is overcoming challenges associated with incorporating additive manufacturing processes for designing composite geometries with optimised material properties. This endeavour is projected to catalyse research efforts in these domains, contributing to the overall progression of technology.

The paper also underscores the need for more studies on the effect of heat treatment methods and emphasises the importance of investigating wear properties, particle size effects, and post-sintering extrusion on the strength of Al/HEAp composites. Interfacial bonding characteristics and strengthening mechanisms between HEAp and the Al alloy matrix require further examination.

A significant research gap exists in the corrosion behaviour of these composite systems, and the paper advocates for comprehensive studies to address this gap. Specifically, research should focus on the effects of production processes, HEAp reinforcement volume fraction, different environmental conditions, intermetallic compound formation, and the influence of heat treatment on corrosion resistance. The weldability, hot deformability, tribological behavior, and damping properties of these HEAp/Al-matrix composites are among the uncharted territories that need to be explored in order to expand their applicability.

Lastly, HEAp possesses certain constraints stemming from their comparatively elevated expense and greater density in comparison to traditional ceramic reinforcements. Research on strategies to address these challenges is anticipated to attract significant attention in the future. An effective approach to overcome this issue is to utilise hybrid reinforcement, which involves combining HEAs and ceramic materials in AMCs. Additionally, the use of computational techniques for modelling experiments is emphasised as an area that needs further exploration to facilitate more cost-effective and efficient research. Furthermore, a current research initiative is underway to decrease the overall manufacturing expenses of high-entropy alloys (HEA). This endeavor has been undertaken by various researchers, including Sharma et al. [112] used the liquid metallurgy route, Jiang et al. [113] used the liquid metallurgy route coupled with the low cost alloying elements, Feng et al. [114], and Xin et al. [115] proposed the use of low-cost alloying element and the mechanical alloying fabrication process. Researchers have devised many cost-efficient methods for manufacturing HEA that possess exceptional mechanical, wear, and corrosion characteristics suitable for diverse applications, including high-temperature and energy-related uses. Research aimed at reducing the overall production cost of high-entropy alloys (HEAs) will significantly decrease the high cost for producing Al/HEAp composites.

8. Conclusion

This review investigates the suitability of high entropy alloys as substitutes for ceramic reinforcements in aluminium matrix composites (AMCs). AMCs reinforced with metallic materials have enhanced wettability characteristics between the matrix and the metallic reinforcement, and this leads to a favourable bonding at the interface between the matrix and the reinforcement. High-entropy alloys (HEAs) are a novel class of metallic systems that enhance the ductility, toughness, and workability of AMCs in comparison to ceramics and amorphous alloys. The ductile nature of the diffusion layer, which is created through volume diffusion at the interface between the HEAp and Al matrix, leads to improved load transfer and load-bearing capacity. Additionally, this layer reduces stress concentration and contributes to the enhancement of the mechanical characteristics of the material. The improvement in mechanical properties was achieved through the implementation of various mechanisms, including grain refining, Orowan strengthening, load transfer strengthening, and dislocation strengthening. The reviewed studies demonstrate a positive correlation between the volume fraction of HEAp reinforcement and the mechanical characteristics of the composites. The most favourable characteristics were seen in the majority of instances while utilising 10-12 wt % HEAp reinforcement, contingent upon the specific manufacturing procedure employed. The functional features of the AMC are primarily determined by the interface bonding strength, interface reaction products, and the morphology of the HEA particles. The various manufacturing techniques have demonstrated the ability to generate a diverse array of microstructural attributes, which exert a substantial influence on their functional capabilities. AMCs reinforced with HEA particles, produced using additive manufacturing, demonstrate enhanced functional characteristics in comparison to AMCs fabricated using traditional liquid and powder metallurgical methods. While the friction stir manufacturing method is effective in generating a strong bond between Al and HEAp at the interface, additive manufacturing techniques have been found to result in a faster solidification process, increase the uniformity of the microstructure, and enhance the characteristics of AMCs. The incorporation of HEAp is found to notably enhance the strength-ductility ratio of AMCs. Remarkably, HEAp bring about significant improvements in the wear and corrosion resistance of AMCs. This report underscores the positive performance outcomes and specific challenges associated with employing HEAp as reinforcements in AMCs. Furthermore, potential directions for future research in this domain are suggested. In summary, the utilization of HEAp as ceramic reinforcement alternatives in AMCs is considered highly promising, positioning them as the optimal choice for designing AMCs with outstanding performance attributes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jmrt.2024.05.153.

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