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# Design and selection of metal matrix composites reinforced with high entropy alloys – Functionality appraisal and applicability in service: A critical review

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A B S T R A C T

Metal matrix composites (MMCs) reinforced with high entropy alloy particulates (HEAps) are a new class of metal-matrix composites that have the promise to meet the demanding requirements of nascent technological applications. Their desirability has been predicated on their favourable combinations of toughness, strength, ductility, and improved workability, which are acknowledged limitations of ceramic-reinforced MMCs. The superior wettability obtained between the metal matrix and the HEAps reinforcement, as well as the HEAps' intrinsic ductility and hardness, have been linked to their improved properties over conventional MMCs. This review discusses the applicability of high entropy alloys as alternatives to ceramic materials for reinforcement of metal matrix composites– Al, Cu, Mg, Ti, and W. The mechanical, corrosion, wear, and thermal properties of MMCs reinforced with high entropy alloy particles (HEAps) were discussed. Their fabrication characteristics and interfacial reactions are also assessed. This report highlights the performance benefits and certain issues associated with HEAps reinforcement application in MMCs. Finally, potential future research directions in this field are suggested.

## 1. Introduction

Technological advancements in manufacturing commercial structural components for the transportation industries have led to the hunt for lightweight, eco-friendly materials with high strength, good corrosion resistance, excellent creep resistance and superior abrasion resistance. [1,2] Metal matrix composites (MMCs) are promising candidates that have been considered for fulfilling this service requirement yearning. This is because of their exceptional attributes, which include a good combination of mechanical and surface properties, amenability to well-established conventional processing techniques and low processing cost. [3,4] Owing to the absence of good property combinations in the monolithic alloy, it is quite difficult to use them satisfactorily for modern-day in service requirements in several engineering applications. However, the ease of achieving tailored property combinations in MMCs have made them attractive in automobile, aerospace, marine, military, structural and building system, biomedical, sports and games recreational equipment and, most importantly, at elevated and cryogenic temperatures. [5–7].

MMCs are conventionally reinforced with ceramic particulates, whiskers or fibres, but particulates of graphite, alumina, silicon carbide, diamond particulates, boron carbide and titanium dioxide are mostly utilised. [3–5,7–9] However, major limitations exist with using these reinforcements. [10,11] These limitations include the segregation of reinforcing particulates, the inherent brittle nature of the ceramic systems, interfacial reaction and poor wettability between the matrix metal and the ceramic materials, which results in poor interfacial bonding and degradation in high abrasion resistance, poor ductility, poor toughness,

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poor workability, poor thermal fatigue and recycling difficulties. These limitations have been a major concern where new structural and stress-bearing components are required. [12,13].

When MMCs are produced, the issues of poor ductility, toughness and formability are caused by the reinforcements' inability to wet with the base metal properly. [7,11,14] Furthermore, low ductility and formability are caused by the segregation or agglomeration of reinforcing elements, [15] reinforcement-induced voids and fractures, particle debonding and cracking in MMCs fabricated via cast and powder metallurgy techniques. [15,16] Previous authors have explored the idea of changing reinforcement type, size and geometries to address these issues in MMCs. [17,18] Other researchers studied using nano-sized reinforcing particles to achieve significant strength gain while keeping ductility, [19] yet others contemplated expanding the notion of employing hybrid reinforcements to address the issue of poor ductility in MMCs. [16,20] Some research groups sought to combine micro and nano-sized reinforcements, [15,20] while others investigated mixing various nano-sized reinforcements when tackling the difficulty of enhancing ductility in MMCs. [21,22] While these techniques have had some degree of success, conventional alloys continue to outperform new composites in terms of ductility, toughness, machinability, and formability. Consequently, transferring the modest gain in ductility and toughness of MMCs to current applications where the ductility and toughness of monolithic alloys are regarded as the ultimate standard remains challenging.

Recently, there have been technical campaigns towards using metallic systems as an alternative reinforcement to these ceramic reinforcements based on the promising results obtained from laboratory studies. [2,19] Using metallic systems as reinforcements in fabricating MMCs has several advantages, including enhanced wettability between the matrix and reinforcement metals, as well as metallurgical bonding between the metal matrix and the reinforcement. This improves the interfacial strength for more effective stress transfer, enhanced ductility and fracture toughness. This improvement is attributed to the inherent ductile nature of the metallic systems and the fact that their usage has no detrimental consequences on other desirable functional properties like corrosion, wear and damping properties. [11] High entropy alloys (HEAs) are a novel type of metallic system made up of many components (usually four or more metallic constituents) in approximately equiatomic ratios. [23,24] Despite their odd chemistry, they exist mostly as simple solid solutions with intriguing and beneficial characteristics. They acquire their distinctive characteristics from four main effects: (1) the sluggish diffusion effect, (2) the severe lattice distortion effect, (3) the high entropy effect, and (4) the cocktail effect. [23–25] Apart from their inherent slow diffusion behaviour and less reactive property, HEAs offer several intriguing characteristics, including high mechanical strength, excellent corrosion resistance, excellent oxidation resistance, remarkable wear resistance and exceptional thermal stability. [23,25] In comparison to ceramics and amorphous alloys, HEAs, in particular, exhibit greater elongation. [25,26] Thus, they are a great reinforcement option in fabricating MMCs (metal-metal) with high-performance indices.

The emphasis of the current review is on the appraisal of the mechanical, corrosion, wear and thermal properties of MMCs reinforced with high entropy alloy particles (HEAps). Their fabrication characteristics and interfacial reactions are also assessed. The critical research questions this review set to provide answers to are: Would HEAp reinforcement truly outperform ceramic reinforcements in MMCs in terms of general mechanical strength? Would the poor ductility and toughness associated with ceramic-reinforced MMCs be sorted without any deleterious effect on other mechanical properties, wear, corrosion and other functional properties if HEAp reinforcements are used in fabricating MMCs? Since there has not been a thorough literature evaluation on the new metal matrix/HEAp composites hitherto served as the impetus for this review's area of concentration. The available review articles on this topic are currently limited to conventional MMCs with ceramics reinforcement or agrowaste derivatives, [9] conventional metallic alloys, shape memory alloys and metallic glasses reinforcements. [11,27,28] Hence, this review effort was undertaken in light of the apparent absence in the literature regarding state-of-the-art reviews on the assessment of MMCs reinforced with HEAps. The next section gives readers a short overview on the applicability of HEAs particles as reinforcement in MMCs.

## 2. Applicability of HEAs particles in MMCs

Ceramics have been known as traditional reinforcing materials in MMCs' property enhancement, especially in terms of strength, hardness and wear resistance. [11] However, the difference in bonding type between the metal matrix and the ceramic reinforcement, inherent brittle nature of the ceramics systems, variations in expansion coefficient and elastic modulus at the interface between ceramic reinforcements and the matrix phase is responsible for the weak interfacial bonding and poor mechanical properties. [29,30] In pursuance of high-performance composites, some authors have employed metallic glasses as reinforcing materials in MMCs. It is widely reported in literature that the techniques of incorporating metallic glass alloy particles have had some degree of success. [29] However, these amorphous alloys are brittle, have high density and are unsuitable for high-temperature applications due to their low crystallisation temperatures, making it difficult to process them during composite fabrication processes. [31].

HEAs exhibit excellent wear, corrosion and high-temperature properties with a good combination of strength and ductility. [32,33] These properties have been attributed to their cocktail and high-entropy effect, sluggish diffusion and severe lattice distortion. [32,34–36] The applicability of MMCs can be increased by exploring new reinforcing materials, potentially enhancing their overall properties. [37] With respect to high-performance reinforcements, HEAs exploit the differentials in atomic sizes, lattice distortion and sluggish atomic diffusion effects to enhance the composite's interfacial bond strength and hardness. [32,38,39] Some authors have reported the suitability of HEAs as reinforcing materials in MMCs due to their superior interfacial bonding characteristics, excellent ductility and toughness over the ceramics systems. [40,41] It has been reported that ceramic materials feature atoms bound together by chemical bonds, with covalent and ionic bonds being the most prevalent. In contrast, metals are characterized by metallic bonds. [11,27,28] The enhanced bonding at the metal-matrix interface in a metal-metal system, in contrast to a metal-ceramic system, significantly diminishes the likelihood of particle cracking or debonding at matrix-reinforcement interface. [11,27,28] Hence, employing reinforcements with a consistent bonding type in MMCs, specifically metallic bonding, serves to mitigate wettability concerns in MMCs. The idea of reinforcing MMCs with HEAps is to improve wetability and integrate the good characteristics of HEAs into MMCs. [37] The next section gives readers the design strategies and processing techniques of MMCs reinforced with HEAps.

### 2.1. Design approach and processing of MMCs reinforced with HEAps

In this section, the design strategies and processing techniques of MMCs reinforced with HEAps are presented. The preceding sections noted that metal matrices dispense applied load to the reinforced particles, thereby enhancing the mechanical strength of the composite material. [42] It has been reported that design and processing methods can be employed to tailor MMCs' structural and functional properties. [42] MMC processing techniques are classified based on the procedures for adding the reinforcing material. [43] Many researchers, including Sharma *et al.* [44] and Bains *et al.*, [42] have noted that the solid and liquid state design approaches are the two prominent methods for producing MMCs. The various approaches involved in the fabrication of MMCs for different applications are presented in Fig. 1.

In the liquid state production process, the reinforcement is added to

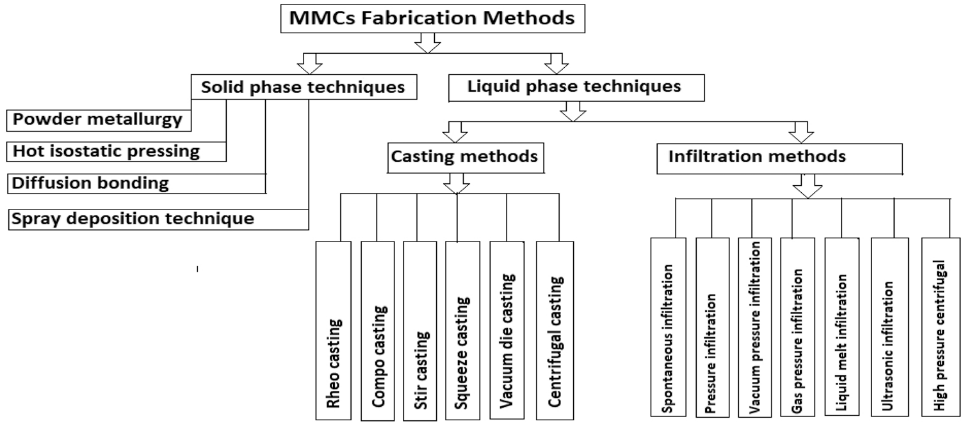


**Fig. 1.** Different approaches and fabrication techniques involved in producing metal matrix composites.

the molten metal matrix and mixed to form the MMC material. [45] The liquid metallurgy route, which consists mainly of liquid melt casting and infiltration approaches, is relatively simple but seldom attains a uniform distribution of reinforcement in the matrix structure. [43,44] The type of liquid state procedure adopted during the production of MMCs depends on the application and desired shape of the product. [44] For instance, centrifugal casting is suitable and often employed for manufacturing cylinders with thin-wall sections. Centripetal forces help distribute the molten matrix containing reinforcement into the intricate mould cavity. [46] Sharma *et al.* [44] produced an AMC with particulate reinforcement using stir casting. The stir casting parameters, such as stirrer speed, stirring period, pouring temperature, type of wetting elements, and preheating of the mould and reinforcing materials, control the interface bonding and dispersion of the reinforcing materials. The authors, however, did not specify the optimum parameters for the fabrication approach. In a similar study, Sahu and Sahu [47] focused on producing stir-cast AMCs and established the stirring process parameters. They reported an optimum stirring speed of 500 rpm and 1000 rpm for single-stage and multistage impellers, respectively. The optimal stirring time was ten minutes, and the optimum reinforcement feed rate was within the range of 0.8 to 1.5 g/sec.

In the solid-state process, MMCs are produced by integrating the matrix material and reinforcing material by the diffusion mechanism and interaction, which occur between the matrix phase and the reinforcement in the solid state. [46] Sintering, diffusion bonding, spray deposition and high-energy ball milling are among the prominent solid-state procedures that can be used to achieve excellent homogeneity between the matrix and the reinforcing phases. [42,44] The solid-state procedures involve integrating powder materials, compaction into a pre-determined shape and sintering the product. For the powder metallurgical route, the production process is often accomplished by preheating the base materials, blending for uniformity, compacting into a desired shape and sintering the product. [48] For example, Li *et al.* [49] produced a Cu matrix composite reinforced with diamond powder using powder metallurgy processing. The deposition of a nano-Cu matrix on diamond particles coated with a nano-sized Ti layer reportedly improved the interfacial bonding between the Cu matrix and the diamond reinforcement. Spray deposition is also a solid-phase composite fabrication method in which the reinforcing materials, usually in the form of fibres, are coated and bonded with the matrix. [42] The comprehensive comparative analysis of the various liquid and solid-state MMC-fabrication methods has been discussed by different authors [44,46,50,51] and is presented in Table 1. Section 3.1.1 presents a succinct overview of processing methods employed in developing MMCs reinforced with HEAps.

**Table 1**
Comparison between the liquid and solid phase metal matrix composites' fabrication approaches.

| Parameters for comparison | Liquid-phase approaches | Solid-phase approaches |
|---|---|---|
| Cost effectiveness [42–44] | Low, generally, this techniques are very cost effective | High - generally, this techniques are very complex, sophisticated and expensive. |
| Matrix-reinforcement bonding[42] | Medium – Unwanted reactions between reinforcement and matrix. | High – No other by-product or unwanted layer is formed between reinforcement and matrix. |
| Applicability [44–47] | Stir casting (mass production of Al matrix composites)Squeeze and compo casting (mass production of automobiles, such as pistons, connecting rods and cylinder heads, and aerospace)Spray casting (production of cutting and grinding tools, electrical brushes and contacts) | Powder metallurgy (small circular objects such as pistons, bolts and valves) Diffusion bonding (structural components, sheets and blades) |
| Composite form [44–46] | Suitable for all forms of reinforcements | Mostly suitable for particulate reinforcements |
| Dispersion of reinforcement in matrix.[46–48] | Medium – uniform particles distribution. | High – uniform particles distribution. |
| Ease of fabrication [44,47] | High | Low |
| Porosity[42] | More voids are found in matrix but with some techniques like squeeze casting this defects are eliminated | No void or other defects are found in matrix. |
| Homogeneous microstructure [42,46] | Medium – possesses less homogeneous microstructure | High – possesses more homogeneous microstructure. |

### 2.1.1. *Fabrication techniques for some HEAp-reinforced MMCs and their effect on mechanical properties*

Metallic particle reinforcements in MMCs exhibit good interface wettability, better adhesion and higher interface bond strength than ceramic particle reinforcements. [52] The inherent ductile nature of metallic reinforcemet, coupled with the fact that the bonding at interfaces is notably stronger in metal-matrix composites reinforced with metals than those reinforced with ceramics has led to improvement in their strength-ductility ratio. [11,27,28] In metal-reinforced metal systems, there is a more consistent interface bonding, enhancing overall strength-ductility ratio compared to metal-ceramic systems. In the latter, the presence of voids creates discontinuities that can act as stress concentration sites, ultimately diminishing the composite strength-ductility ratio in contrast to systems with a more continuous interface bonding. This development has led to using HEAps as reinforcements in MMCs in recent years. Several authors, including Ma *et al.*, [53] Yuan *et al.*, [54] Li *et al.*, [18] Chen *et al.*, [55] and Luo *et al.*, [52] have already explored several techniques for processing MMCs with HEAp reinforcements. Some of these studies adopted the powder metallurgy approach, which involves mechanical alloying via powder ball milling and subsequent sintering by spark plasma, microwave or hot pressing to produce finished or semi-finished products of HEAp-reinforced composites [56].

Ma *et al.* [53] synthesised AA5052 MMCs containing $Al_{0.6}CoCrFeNi$ HEAp reinforcement using vacuum hot pressing sintering. The composite's modulus of elasticity and hardness increased compared to the matrix. Yuan *et al.* [54] adopted the spark plasma sintering approach to fabricate 2024 AMCs reinforced with CoCrFeMnNi HEAps and observed an improvement in the hardness due to the fine dispersion of the HEAps in the matrix structure. Satyanarayana *et al.* [57] fabricated a CoCrFeMnNi HEAp to use as reinforcement particles in a tungsten-heavy alloy (WHA) composite. Mechanically alloyed CoCrFeMnNi HEAps and elemental tungsten (W) powder were combined in a high-energy ball mill. Various heat processes with different heating rates were used to consolidate the mixture in the order of the traditional sintering method, microwave sintering technique and spark plasma sintering. Their results demonstrate that W grain growth is constrained by increased heating rate, which lowers the proportion of the Cr-Mn-rich phase. Moreover, compared to the other two competing methods, microwave sintering (1962 MPa) and traditional sintering (1758 MPa), spark plasma sintering demonstrated better compressive strength (2041 MPa), which can be ascribed to finer W-grains and a lower percentage of the Cr-Mn rich oxide phase. Chen *et al.* [55] designed and fabricated a Cu matrix composite reinforced with AlCoNiCrFe HEAps using the powder metallurgy technique. The study observed that MMCs with HEAp reinforcements are stronger than their counterparts with metallic glasses reinforcements.

Apart from pressing and sintering methods, friction stir processing has also been adopted. Li *et al.* [18] produced AA5083 composite material reinforced with $Al_{0.8}CoCrFeNi$ HEAps via friction stir welding. The strength of the matrix material improved. Yang *et al.* [58] manufactured an AA5083 metal matrix with AlCoCrFeNi HEAps as reinforcements using the submerged friction stir processing method stipulated in Adiga *et al.* [59] The reinforcing HEAps were coherent with the AA5083 matrix structure and the resulting composites' microstructures were characterised by equiaxed fine grains. Consequently, the strength metrics of the composite with HEAps increased compared to the matrix material. In a related study by Gao *et al.*, [60] using friction stir processing and integrating FeCoNiCrAl HEAps in an Al5083 metal matrix enhanced the wear resistance and hardness characteristics of the matrix.

In a very recent study conducted by Luo *et al.* [52], a liquid metallurgical approach was utilised to fabricate AA1050 MMCs reinforced with $Al_{0.5}CoCrFeNi$ HEAps using the stir casting technique. The tensile strength of the composite increased by 74.3% compared to the matrix. Chitturi *et al.* [61] investigated the mechanical properties of 6061 Al MMCs reinforced with FeCoCrNiMo HEAps and boron carbide, fabricated using manual stir casting. The strength, hardness and toughness of the composites increased tremendously with the corresponding increase in the HEAp reinforcement's volume fraction. According to Karthik *et al.* [62] and Praveen Kumar *et al.*, [63] the MMCs reinforced by HEAps and boron carbide had improved mechanical characteristics compared to the pure 6061 Al material.

It can be inferred from the articles presented in this section that integrating HEAps as reinforcement in MMCs is quite promising as it greatly improves the MMCs' mechanical properties. It was observed that very few authors compared their results with conventional MMCs; those that did report that the strength-ductility ratio improved compared to conventional MMCs. The mechanism by which HEAps improve the functional properties of the composites can be elucidated by studying the microstructural interaction between the matrix and the reinforcement phases, which will be discussed in the following section.

### 2.2. HEA particle interaction and evolution of interfaces in HEAps reinforced MMCs

Ceramic particle reinforcements in MMCs have serious limitations associated with agglomeration, cracking, the formation of deleterious interfacial compounds like $Al_4C_3$ and particle fragmentation. These challenges have led to considering HEAs as reinforcements in MMCs. [64] This consideration is motivated by the good interface bonding between metallic reinforcements and metal matrices. [65] To optimise the functional and mechanical properties of HEAp-MMCs, there is a need to examine the interaction of HEAps with the metal matrix and the mechanisms driving their microstructural evolution.

The geometry of the reinforcing particles, and the adhesion between the matrix and the reinforcing particles, i.e., the interfacial characteristics, influence the composites' plasticity. [56] The interfaces between the matrix and reinforcing particles are preferential sites for stress concentration and failure initiation in particle-reinforced MMCs. [66] Several studies, which are summarised in the succeeding paragraphs according to the similarity in their production techniques, have reported on the different microstructural manifestations at the HEAp-MMC interface.

Considering the studies conducted on hot pressed or sintered HEAp-reinforced MMCs, there were cases where the interfacial layer may either evolve or not. For example, Chiu and Chang [67] studied the production and characterisation of AZ91 Mg-based alloy matrix composites reinforced with 10 wt% $Al_{0.5}CoCrFeNi_2$ HEAps and SiC particles. The composites were prepared using spark plasma sintering at 300 °C. The microstructure of the Mg-based alloy matrix composite samples was characterised using a JEOL JSM-6500 F scanning electron microscope, and the evolved phases were analysed by X-ray diffraction using Cu Kα radiation. The microstructures of the Mg-based alloy matrix composites consisted of $Mg_{17}Al_{12}$, $\alpha$-Mg and face-centred cubic (FCC) phases, and there was no deleterious interfacial interaction between the HEAps and the Mg alloy matrix. The porosity of the formed Mg-based alloy matrix composites influenced the interfacial bond strength between the Mg matrix and the HEAps. Fig. 2(a-d) shows the scanning electron micrographs of the Mg-based alloy matrix composite samples. The particles' interface with the AZ91 matrix structure shows some porosity in the composite microstructure (Fig. 2a). Fig. 2b shows the presence of the $Mg_{17}Al_{12}$ phase and Mg precipitates in the AZ91 matrix. The microstructure in Fig. 2c shows the distribution of HEAps in the AZ91-HEAp composite. The particles were evenly distributed in the matrix structure (Fig. 2d), showing that there is no clear boundary of HEAps in the AZ91 matrix in the microstructure and identifies the $Mg_{17}Al_{12}$ phase as the brighter precipitate (designated B) and Mg precipitates as the grey patches (designated A).

Gao *et al.* [68] synthesised and characterised 7075 AMCs reinforced with varied volume fractions (5, 10, 15 and 20 vol%) of FeCoCrNiAl HEAps using vacuum ball milling and vacuum hot pressing sintering. The microstructures and phase components of the samples were analysed using the D8 ADVANCE (Bruker AXS Co.) X-ray diffractometer and transmission electron microscopy. Uniform distribution of HEAp reinforcements in the 7075 Al matrix was achieved (Fig. 3a). Fig. 3b shows a noticeable interface or boundary between the HEAps and the 7075 Al matrix. Dislocations were also observed in the microstructure due to the difference in the coefficient of thermal expansion between the HEAps and the 7075 Al matrix. Similar observations were reported by Li *et al.* [69] when they examined the microstructure of the AlCuCrFe HEAp-reinforced Al matrix. HEAps were homogeneously dispersed within the Al matrix. Also, they established that there was an amorphous bonding layer of 1 to 5 nm thick at the interface between the AlCuCrFe

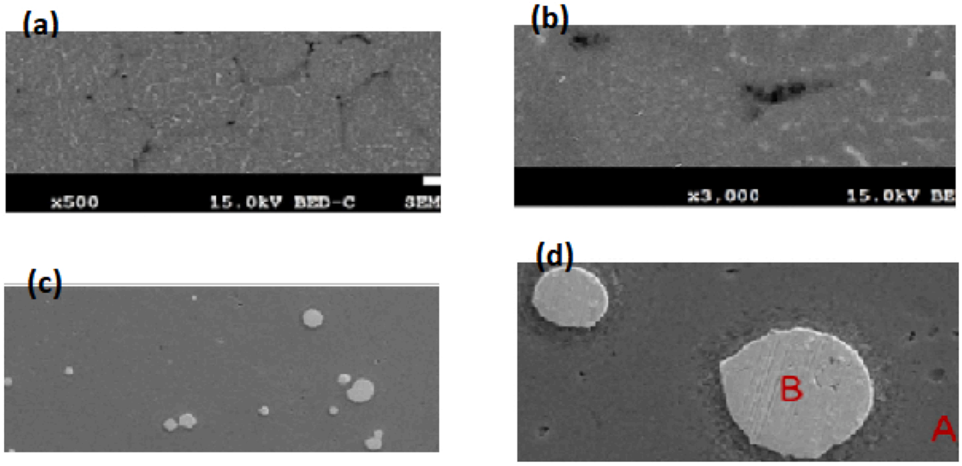


**Fig. 2.** Scanning electron micrographs showing (**a**) particle boundaries in the AZ91 metal matrix, (**b**) Mg precipitates in the AZ91 matrix, (**c**) the distribution of high entropy alloy particles in the AZ91-HEAp composites, and (**d**) the boundary of high entropy alloy particles in the AZ91 matrix [67] culled with permission from Elsevier.

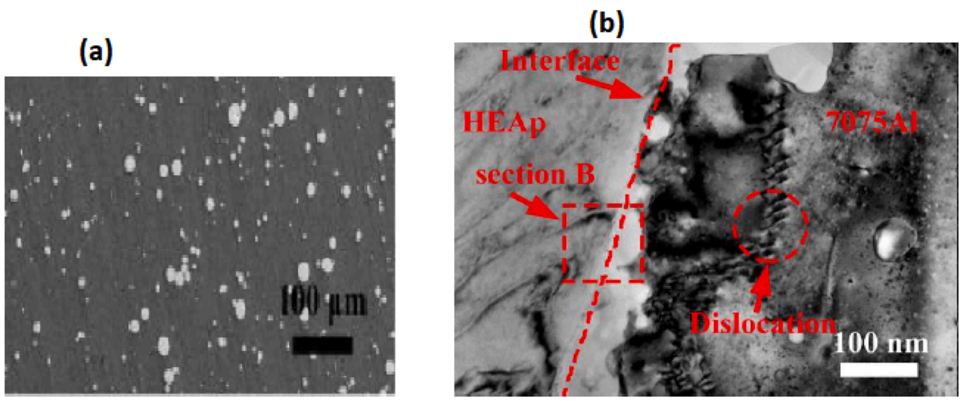


**Fig. 3.** Composite's microstructure showing (a) the morphologies and distribution of the high entropy alloy particle reinforcements (5 vol%) in the 7075 Al matrix and (b) transmission electron micrograph revealing the interfacial interaction between the high entropy alloy particles and the 7075 Al matrix. [68] culled with permission from Elsevier.

HEAps and the Al matrix. Xiong *et al.* [70] characterised Ti6Al4V matrix composites reinforced with CoCrFeNiMo HEAps fabricated via the powder metallurgy technique using a spark plasma sintering system for sintering the composites. The study defined the diffusion boundary layer region as consisting of three zones: high entropy particles (zone I), the interface diffusion layer (zone II) and the matrix phase (zone III). The interface diffusion layer comprised intermetallic compounds (the σ–phase) and an orderly FCC phase.

The evolution of interfacial layer and equiaxed properties have been reported for HEAp-reinforced MMCs produced via processes involving deformation such as extrusion or friction stir process. For example, Huan *et al.* [71] studied the properties of 6061 AMCs reinforced with $AlFeNiCrCoTi_{0.5}$ HEAps prepared by extrusion. The microstructures of the composites were analysed using scanning electron microscopy. HEAps with reinforcement less than 10 vol% reduced the defects in the 6061 Al matrix. However, HEAps with reinforcements up to 15 vol% result in loss of strength by agglomeration of the reinforcing particles in the matrix structure. Li *et al.* [18] reported that including $Al_{0.8}CoCrFeNi$ HEAps in the Al matrix by friction stirring led to the formation of equiaxed fine grains in the composite structure. The grain refinement was attributed to dynamic recrystallisation caused by high temperature and severe plastic deformation during friction stirring. The study maintained that atomic diffusion at the interface between the reinforcement and the matrix occurs with diffusion fluxes of Co, Cr, Fe and Ni atoms from HEAps toward the Al matrix and vice versa. This interfacial interaction between the matrix and the reinforcing phase led to the formation of an interfacial zone, contributing to effective load transfer. This report concurs with the observations of Yang *et al.*, [58] where 5083 AMCs reinforced with 10 vol% AlCoCrFeNi HEAps were fabricated using submerged friction stirring. The study noted the occurrence of dynamic recrystallisation leading to the formation of equiaxed fine grains. The microstructure analysis revealed a dual interface diffusion layer at the HEAp/5083 Al matrix interface; one near the HEAps consisting of FCC + T-phases with a thickness of 100 nm while the other near the Cr-depleted AlCoCrFeNi HEAps also has a thickness of 100 nm. The observed increase in the strength and ductility of the composite products was attributed to these phase characteristics.

In conventional MMCs reinforced with synthetic ceramic particulates, forming an interfacial layer during production processes is undesirable because it often degrades the composites' mechanical properties. The phase constituents and morphology of the interfacial layer formed when developing HEAp-reinforced MMCs vary. Therefore, the resulting interfacial layer can either improve or degrade the performance of this grade of MMCs. Various observations on the influence of an interfacial layer on composites' performance have been published. Lu *et al.* [72] compared the effect of SiC and $CoNiFeCrAl_{0.6}Ti_{0.4}$ HEAp reinforcements in 2024 AMCs and found that the HEAp-reinforced 2024 Al matrix had better mechanical properties than the SiC-reinforced 2024 Al matrix.

The formation of deleterious compounds such as $Al_4C_3$ in Al/SiC composites has been widely reported in literature. The Al/HEAps composite was reported to have higher strength (712 MPa), and better plasticity than the Al/SiC composite, which was ascribed to the inherent toughness, high strength and deformability in nano-crystalline HEAps, as well as excellent wettability between the reinforcing HEAps and the Al matrix. A diffusion interaction between the interface of the HEAps and the 2024 Al matrix observably led to the formation of an interfacial layer containing Al, Cu, Co and Ni with a layer thickness of 200 nm and depth of about 130 nm. This indicates that a suitable interface reaction layer contributed to improving the fracture toughness of the Al/HEAps composite. Yuan *et al.* [73] studied the influence of thermal treatment on the properties and interfacial interaction between the 5052 Al matrix and 7 vol% of $Al_{0.6}$CoCrFeNi HEAp reinforcement. Young's modulus and the hardness of the 5052 Al matrix improved because of the formation of a core-shell structure at the interface between the HEAp reinforcements and the matrix structure. This observation concurs with the findings of Liu *et al.* [34] Yuan *et al.*, [54] and Liu *et al.* [74] studied the microstructure and properties of AlCoCrFeNi HEAp-reinforced Cu matrix composites prepared by spark plasma sintering. It was confirmed that a core-shell structure forms in the reinforcing phase due to the interfacial diffusion between the Cu matrix and the HEAps, improving plasticity in the composite. Also, the diffusion of Al, Co, Cr, Fe and Ni from the HEAps to the Cu matrix greatly increased the composite's yield strength due to the solid-solution strengthening of the matrix by the diffusing elements from the HEAps. Liu *et al.* [34] fabricated an Al/AlCoCrFeNi HEAp composite via spark plasma sintering and reported the formation of an interfacial layer at the matrix-reinforcement interface. The interfacial layer enhanced the composite's mechanical properties, and the yield strength was 42% higher than the composite without an interfacial layer. The yield strength (96 MPa) and compressive strain (36%) for the composite without an interfacial layer were lower than the yield strength (137 MPa) and compressive strain (50%) of the composite with an interfacial layer. This was ascribed to effective stress-state transformation during deformation from an iso-stress to iso-strain condition in the composite with an interfacial layer. [34] Yuan *et al.* [54] noted that the interface diffusion layer formed at the interface between the CoCrFeMnNi HEAps and the 2024 Al matrix was about 6 nm thick, which is related to the spark plasma sintering processing parameters (such as sintering mode, temperature and time). Ma *et al.* [53] studied the mechanical behaviour and interface interaction between a 5052 Al matrix reinforced with $Al_{0.6}$CoCrFeNi HEAps prepared by vacuum hot pressing sintering. The composite samples were annealed, and the evolved microstructures were analysed using cold field emission scanning electron microscopy and X-ray diffractometry. Interfacial interaction occurred at the HEAp/matrix boundary by diffusion, leading to the formation of a diffusion boundary layer at the HEAp/matrix interface. The boundary layer region at the HEAp/matrix interface consisted of $Al_{13}Co_4$-type, $Al_9Co_2$-type and $Al_{18}Cr_2Mg_3$ intermetallic phases, as illustrated in Fig. 4. The evolution of these intermetallic phases greatly helped form an excellent metallurgical bond between the HEAps and the Al matrix, enhancing the composites' mechanical properties. The thickness of the diffusion boundary layer increased parabolically with annealing temperature and time. However, as seen in Fig. 4, as the annealing temperature and time continue to increase, a ring-shaped diffusion layer slowly develops at the HEAp/matrix interface, which dissolves gradually, leading to the delamination of the diffusion layer and eventual dissolution of some HEAps in the matrix structure. The dissolution of the interfacial layer due to annealing reduced the load carrying capacity of the Al/HEAps composite. The authors concluded that the composites' mechanical behaviour was sensitive to the phase characteristics of the diffusion boundary layer region.

Wang *et al.* [75] observed that the diffusion at the $Al_{0.9}$CoCrFeNi HEAp/Al-10Si-Mg matrix interface, which takes place at high temperatures, results in the emergence of a brittle σ phase, decreasing the composites' plasticity. Yang *et al.* [76] studied the strength metrics,

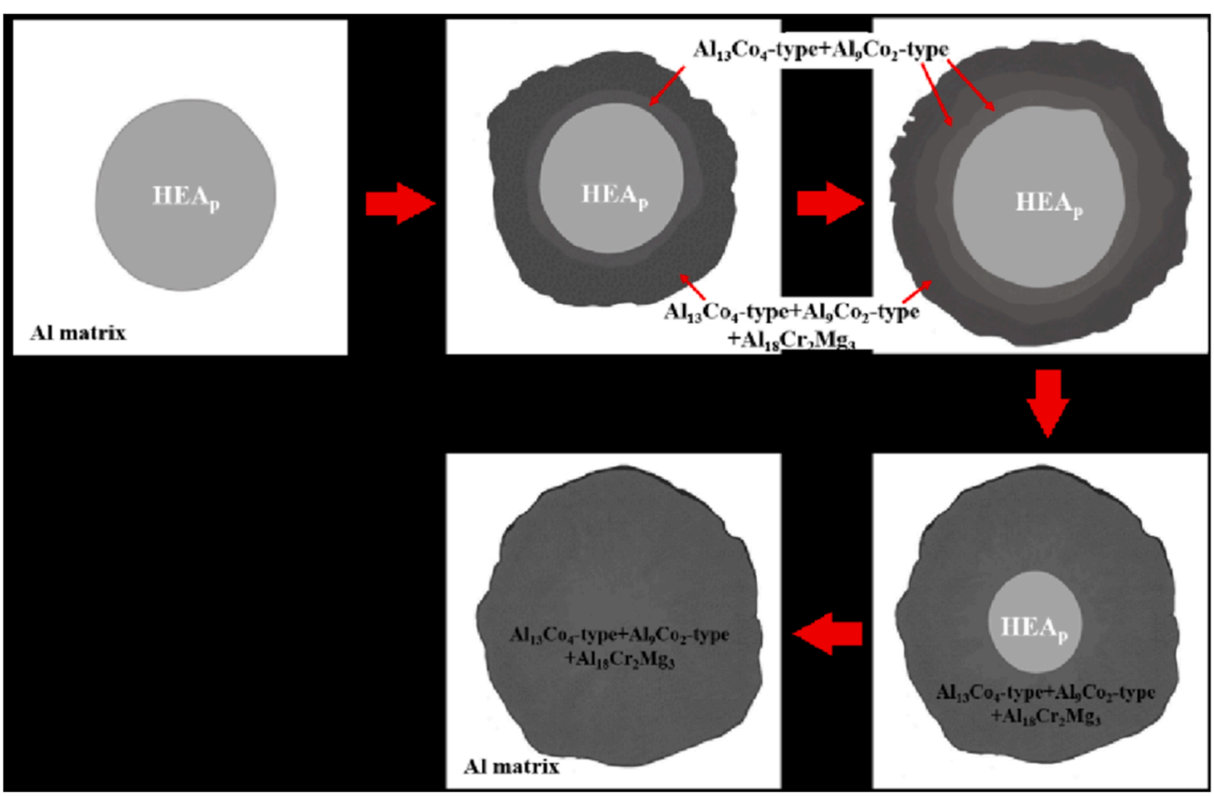


**Fig. 4.** Effect of annealing conditions on the composition and pattern of the interface diffusion layer region in Al/high entropy alloy particle (HEAp) composites [53] culled with permission from Elsevier.

fracture behaviour and interface evolution of a spark plasma sintered Al-based composite reinforced with AlCoCrFeNi HEAps. The interface evolved a two-layer structure: $Al_{13}(CoCrFeNi)_4$ made up the interfacial reaction phase closest to the HEA reinforcement particles, and $Al_9(CoFeNi)_2$ and $Al_{18}Cr_2Mg_3$ made up the interface reaction phases closest to the Al matrix. The introduction of HEAps as reinforcement improved the composites' yield strength while there was a marginal decrease in their tensile and elongation properties. The fracture occurred near the HEAps at the interfacial reaction layer, displaying brittle failure features. The low plastic deformability of continuously dispersed $Al_{13}(CoCrFeNi)_4$ and the increased level of stress concentration at the interface layer near the HEA-reinforcing particles are ascribed as the mechanism responsible for the tensile fracture of the Al/HEAp composite. Zhao *et al.* [77] investigated the impact of HEAp morphology on the characteristics and microstructure of cast Al alloy reinforced with $Al_{0.23}Cu_{0.75}FeCoNi$ HEAps. HEAp reinforcements with flake morphology have a high tendency to agglomerate in the matrix but act as stress raisers and failure sites in the composite's structure. It was also observed that HEAps with ellipsoidal morphology promote the uniform dispersion of the secondary phase particles within the Al matrix and inhibits interfacial stress concentration between the HEAps and the Al matrix.

Table 2 summarises the evolved microstructures and interactions between the metal matrix phase and HEAp reinforcements. It can be deduced from the articles reviewed that the inclusion of HEAps as reinforcements in MMCs improves the overall mechanical properties including ductility and toughness of the matrix most especially when the amount of HEAps added is not more than 10 vol%. It can be concluded from the works reviewed so far that the interaction at the interface between HEAps and the metal matrix leads to the formation of a diffusion layer, which may either enhance or degrade the interfacial bonding between the matrix and the HEAps.

For some of the studies examined, the interfacial diffusion layer in HEAp-MMCs enhanced the composites' mechanical properties, resulting in their effective load transfer and improved ductility. Different interface products, a function of the composites' composition, are formed at the diffusion layer between the HEAps and the matrix structure. However, because some of the diffusion interface layer could also degrade the performance of the composites, the mechanism driving the formation of these diffusion interfacial layers should be extensively investigated to gain an understanding on how they can be controlled or manipulated to improve the performance of HEAp-MMCs.

Another notable observation from this section is that although many HEAp-reinforced MMCs show promising combination of strength and ductility, most of these studies failed to compare their result with conventional MMCs reinforced with synthetic ceramics. Only Chui and Chang [67] conducted a comparative study between SiC and $Al_{0.5}CoCrFeNi_2$ HEAps in Mg-based MMCs. To juxtapose the results obtained from the reviewed articles, we tried to compare the results from MMCs/HEAp composites with conventional MMCs in Table 3. It can be deduced that HEAp-reinforced MMCs have superior properties in terms of strength and ductility metrics than MMCs reinforced with synthetic ceramics like SiC, $Al_2O_3$, $B_4C$ and $TiB_2$. This trend already puts the use of HEAps reinforcement in MMC design one step closer to solving the strength-ductility trade-off problem associated with MMCs.

## 3. Properties of high entropy alloy-reinforced metal matrix composites

### 3.1. Mechanical properties

In metallic-based composites reinforced with HEAps, the following strengthening mechanisms typically take place: enhanced stress transfer by the matrix phase to the reinforcing phase, the thermal mismatch effect, dislocation strengthening, grain boundary strengthening (Hall-

**Table 2**
Summary of the evolved microstructures and interactions between the metal matrix phases and high entropy alloy particle reinforcements.

| Composite matrix | High entropy alloy particles (HEAps) use for reinforcements | Processing techniques | Microstructural evolution at the matrix/HEAp interface | Reference |
|---|---|---|---|---|
| AZ91 Mg-based alloy | 10 wt% $Al_{0.5}CoCrFeNi_2$ HEAps and SiC | Spark plasma sintering | Evolved microstructure consists of $Mg_{17}Al_{12}$, α-Mg, and face-centred cubic phases without any deleterious interfacial interaction between the HEAp and the Mg-based alloy matrix. | [67] |
| 7075 Al matrix | Varied volume fractions (5, 10, 15 and 20 vol%) of FeCoCrNiAl HEAps | Vacuum ball milling and vacuum hot pressing sintering | A noticeable interface appeared at the boundary between the HEAps and the 7075 Al matrix. Dislocations were observed in the HEAp/matrix interface, which was due to the variation in the coefficient of thermal expansion between the HEAps and the 7075 Al matrix. | [68] |
| 6061 Al matrix | $AlFeNiCrCoTi_{0.5}$ HEAps | Extrusion | 10 vol% HEAps reduced the microstructural defects in the 6061 Al matrix. | [71] |
| Al matrix | $Al_{0.8}CoCrFeNi$ HEAps | Friction stirring process | Equiaxed fine grains occur in the composite structure via dynamic recrystallisation. Interaction occurs at the HEAp/matrix interface, leading to the formation of an interfacial zone of certain thickness by diffusion fluxes of Co, Cr, Fe and Ni atoms from the HEAps toward the Al matrix and vice versa. | [18] |
| 5083 Al matrix | 10 vol% AlCoCrFeNi HEAps | Submerged friction stirring | The composite's microstructure consists of dual interface diffusion layer regions at the HEAp/5083 Al matrix interface. One interface diffusion layer exists near the HEAp consisting of face-centred cubic + T-phases with a thickness of 100 nm while the other interface diffusion layer occurs near the Cr-depleted AlCoCrFeNi HEAps also with a thickness of 100 nm. Equiaxed fine grains occur in the composite structure via dynamic recrystallisation. | [58] |
| 2024 Al matrix | SiC and $CoNiFeCrAl_{0.6}Ti_{0.4}$ HEAps | Powder metallurgy | Formation of an interface diffusion layer containing Al, Cu, Co and Ni with a thickness of 200 nm at the HEAp/matrix interface. | [72] |
| 5052 Al matrix | $Al_{0.6}CoCrFeNi$ HEAps | Vacuum hot pressing sintering | Interfacial interaction occurs at the HEAp/matrix boundary by diffusion leading to the formation of a diffusion boundary layer at the HEAp/matrix interface. The boundary layer region at the HEAp/matrix interface consists of $Al_{13}Co_4$-type, $Al_9Co_2$-type and $Al_{18}Cr_2Mg_3$ intermetallic phases. | [53] |
| Ti6Al4V matrix | CoCrFeNiMo HEAps | Spark plasma sintering | The diffusion boundary layer region has three zones: high entropy particles (zone I), an interface diffusion layer (zone II) and the matrix phase (zone III). The interface diffusion layer consists of an intermetallic compound (the σ-phase) and an orderly face-centred cubic phase. | [70] |
| 5052 Al matrix | 7 vol% of $Al_{0.6}CoCrFeNi$ HEAps | Spark plasma sintering | A core-shell structure forms at the interface between the HEAp reinforcements and the matrix structure. | [73] |
| Cu matrix | AlCoCrFeNi HEAps | Spark plasma sintering | A core-shell structure forms in the reinforcing phase due to interfacial diffusion between the Cu matrix and the HEAps. | [74] |

**Table 3**
Comparing the mechanical properties of metal matrix composites reinforced with high entropy alloy particles with metal matrix composites reinforced with ceramics.

| High entropy alloy particle (HEAp) reinforcements | Properties | Ceramic particles reinforcement | Properties |
|---|---|---|---|
| AZ91Mg/10 wt% $Al_{0.5}CoCrFeNi_2$ | [67] Hardness = 138 HV Compressive yield strength = 209 MPa Failure strain = 13.7% | AZ91Mg/SiC | [67] Hardness = 123 HV Compressive yield strength = 204 MPa Failure strain = 12.2% |
| 7075 Al/10 vol% FeCoCrNiAl | [68] Flexural strength = 640 MPa Fracture toughness = 13.67 $MPa.m^{1/2}$ | Al 5083/$B_4C$ | [78] Strain at fracture = 2.5% |
| 6061 Al/10 vol% $AlFeNiCrCoTi_{0.5}$ | [71] Hardness = 70.3 HV Tensile strength = 188 MPa | Al 5083/$B_4C$ | [79] Strain at fracture = 7.2% Compressive strength = 473 MPa |
| 5083 Al/ $Al_{0.8}CoCrFeNi$ | [18] Yield strength = 200 MPa, Ultimate tensile strength = 371 MPa, Elongation = 18.8% | 5083 Al/10 wt % SiC | [80] Ultimate tensile strength = 134 MPa, Elongation = 8.6% |
| 5083Al /10 vol% AlCoCrFeNi | [58] Elongation = 18.8% | 356Al/3 vol% nano-$TiB_2$ | [81] Ultimate tensile strength = 283 MPa, Elongation = 2% |
| 2024 Al/ $CoNiFeCrAl_{0.6}Ti_{0.4}$ | [72] Failure strain ≈ 7.5% at 10 vol% HEAps | 2024 Al/SiC | [72] Failure strain< 6.0% at 10 vol% SiC |
| 5052 Al/ $Al_{0.6}CoCrFeNi$ | [53] Compressive strength = 325 MPa Hardness = 82.8 HV | A-356.2 Al/ 2 wt% rice husk ash | [82] Elongation to failure = 3.37% Tensile strength = 174.6 MPa |
| Ti6Al4V/ CoCrFeNiMo | [65] At 4.5 wt% HEAps Elongation to failure = 8.8% Ultimate tensile strength = 1150 MPa | A356 Al/Ti-SiC | [83] Ultimate tensile strength = 228 MPa Yield strength = 131 MPa Failure strain = 8.5% |
| Cu/10 vol% AlCoCrFeNi | [74] Yield strength = 265± MPa Elongation = 15.3±0.2% | A356 Al/Cr-SiC | [83] Ultimate tensile strength = 175 MPa Yield Strength = 101 MPa Failure strain = 5.3% |
| W/FeNiMnAlW | [56] Maximum compressive strength = 1241 MPa Maximum plastic strain = 15% | A356 Al/Cu-SiC | [83] Ultimate tensile strength = 168 MPa Yield strength = 99 MPa Failure strain = 6.7% |

Petch effect) and Orowan strengthening. [41,67,70,83,84,85] The mechanical properties based on the type of matrix material will be discussed in the following sub-sections, as well as the influence of HEAps on the strength-ductility ratio.

### 3.1.1. Aluminium matrix

Ceramic reinforcements such as $Al_2O_3$, SiC, $TiB_2$ and $B_4C$, among others, are commonly employed as reinforcement materials in MMCs because of their outstanding spectrum of properties, such as excellent strength and stiffness and outstanding corrosion resistance. [55,86,87] The application of these ceramic materials as reinforcement in MMCs increased their strength. Nevertheless, the agglomeration of this ceramics reinforcement, the poor wettability between the metallic matrix and the ceramics reinforcement, and porosity formation, as well as the brittle characteristic inherent in these ceramic systems, are the major drawbacks in the conventional MMCs produced with ceramics reinforcement. A significant disparity between the coefficients of thermal expansion of ceramic materials and the metallic matrix causes the reinforcing phase to fracture during cooling. Metallic glasses have stronger and more durable metallurgical bonding with the MMCs than ceramic reinforcement; several researchers have investigated using them as reinforcement to solve the shortcomings of ceramic reinforcement. [88–90] [91,92] However, their relatively low crystallisation temperature makes them not applicable to heat-treatable AMCs, thereby limiting their usage. Hence, it is believed that HEAs should exhibit better behaviour as reinforcement because of the high strength and exceptional high-temperature strength of the HEAps.

*3.1.1.1. Powder metallurgy route.* HEAp reinforcement, according to studies conducted by various researchers, significantly enhance the mechanical strength of the Al-based composite compared to conventional ceramics reinforcement. Also, HEAps are receiving much attention, more than metallic glass, [93,94] conventional alloys and pure metals [60] because of the HEAps' exceptional high-temperature strength [95]. Ogunbiyi *et al.* [96] investigated $Fe_{1.2}NiCrCoAlTi_{0.8}$ HEAp-reinforced AA7075 AMCs and observed a tangible balance of their properties. They showed that the HEAp alloy significantly affected micro-hardness, tensile strength, percentage elongation, elastic modulus, and flexural and impact strength (Fig. 5). Huang *et al.* [97] noted that the evolution of intermetallic $Al_{45}(Cr,V)_7$ and $Al_3Ti$ phases in the AlCrTiV HEAp-reinforced AMCs significantly improved the composite's strength metrics, the ultimate tensile strength (UTS) and the yield strength. The improvement was ascribed to grain size reduction due to the reinforcement particles that serve as heterogeneous nucleation sites during solidification.

Maneesh *et al.* [93] developed an AlFeCuNiMgZn HEAp-reinforced AMC through the powder metallurgy route. The composite showed improved hardness as the weight percentage of the HEAp reinforcement increased. Adding the HEAps reduced the porosity in the resulting composite, and this was responsible for the composite's high hardness values. Prabakaran *et al.* [98] showed a similar result when they synthesised CrMnFeNiCu HEAps with AA6061 AMC via the same method. They further observed that the sintering temperature and time significantly affected the properties of the HEAp-reinforced AMCs. In a similar study via the powder metallurgy route, Prakash *et al.* [93] investigated an AlCoCrCuFe HEAp-reinforced AMC. The highest micro-hardness value of 71.3 HV was obtained by incorporating 15 wt% HEAps, demonstrating an increase of 89.63% over unreinforced Al. The observed strength enhancement was ascribed to the HEAps' excellent hardness properties, which might prevent dislocation motion during plastic deformation and result in discontinuities in the slip plane. Wang *et al.* [99] explored using spark plasma sintering in fabricating Al/HEAp composites by producing Al-based composites reinforced with CuZrNiAlTiW HEAps. The composites showed improved mechanical properties in terms of yield strength, hardness and fracture strength

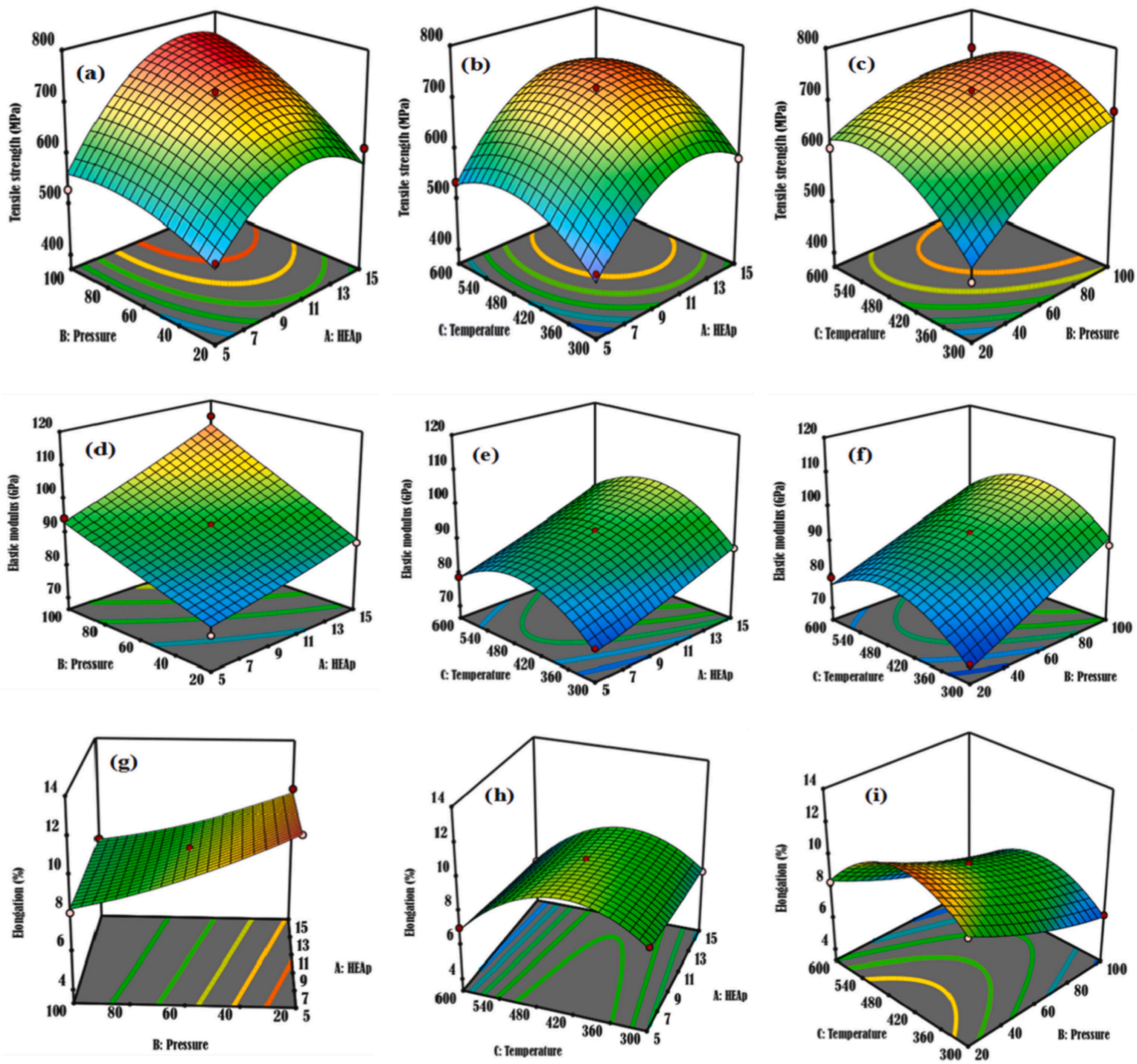


**Fig. 5.** Surface plots for tensile strength indicating (a) high entropy alloy particle (HEAp) vs sintering pressure at 450ºC constant temperature, (b) HEAp vs sintering pressure at 60 MPa constant pressure, and (c) sintering pressure vs sintering temperature at a constant 10 wt% HEAp; elastic modulus showing (d) HEAp vs sintering pressure at a constant temperature of 450ºC, (e) HEAp vs sintering temperature at a constant pressure of 60 MPa, and (f) sintering pressure vs sintering temperature at a constant 10 wt% HEAps; modulus; and (g to i) show the interactions between HEAps and sintering pressure at constant temperatures of 450ºC, 60 MPa, and 10 wt% HEAps.
[96] culled with permission from Elsevier.

compared to unreinforced aluminium alloy. Yuan *et al.* [54] also assessed 2024 Al alloy-based composites fabricated by spark plasma sintering and strengthened with CoCrFeMnNi HEAps, showing that the composites' hardness increased by adding the HEAps. The percentage increment was approximately 63.7%, which was strongly attributed to the impact of the reinforcement particulate and the generally fewer sintering flaws in the composite produced. The inter-diffusion layers reduced the sintering defects and produced a gradient interface microstructure, which helped to reduce stress concentration sites, improving the composite's effective load transfer and bearing capacity.

In recent times, there has been a utilization of ceramic nanopowders for enhancing the strength of MMCs. The Orowan strengthening mechanism suggests that finer particles are more effective in improving strength-ductility properties. [51,79] However, achieving proper dispersion of ceramic nanoparticles in metal melts is challenging. The loosely packed nanoparticle clusters may trap air or vapor within voids, becoming nuclei for cavitations. The cluster size varies from nano to micro due to attractive forces among ceramic nanoparticles and poor wettability between ceramic nanoparticles and the metal melt. [51,79] In the fabrication of metal matrix nanocomposites, the choice of nanoparticles reinforcement is crucial. It is essential to ensure good wettability between nanoparticles and metal melts to attain well-dispersed nanoparticles in the metal matrix nanocomposites. Lu *et al.* [100] studied the mechanical characteristics of a powder metallurgy-produced nano-crystalline $CoNiFeCrAl_{0.6}Ti_{0.4}$ HEAp-reinforced Al-based composite (0, 7.5, 15 and 30 wt% HEAp additions). The HEAps were evenly distributed within the Al matrix, which was ascribed to the grain refinement and the observed increment in mechanical strength of the 2024 Al-based composite. This is because the nano-crystalline-HEAps brought about the pinning effects, which impede the movement of the grain boundaries, and the work-hardening effects, which are due to the treatment operations given to the composite (Fig. 6). Finally, the authors established that when the mechanical properties of the produced Al/nano-crystalline-HEAp composites were compared with that of the AMCs reinforced with conventional ceramic particles, nano-crystalline-HEAps is a promising reinforcement candidate for Al-based composites. It was also reported that Al/nano-crystalline-HEAp composites exhibited a ductile fracture mode characterised by hollow dimples.

Chen *et al.* [101] investigated the effect of HEAps and milling duration on the microstructure and mechanical properties of an Al-based composite reinforced with 7.5 wt% $CoNiFeAl_{0.4}Ti_{0.6}Cr_{0.5}$ HEAps. Compared to unreinforced 6061 Al, the introduced HEAps significantly enhanced the composites' strength metrics, which was linked to grain size reduction. Nonetheless, milling time considerably influences HEAp particle dispersion within the matrix, grain structure and the mechanical properties of the sintered composites. The combination of various strengthening effects, such as the Hall-Petch, effective load transfer, Orowan strengthening mechanism and geometrically needed dislocations, were ascribed to the composites' increase in strength. Finally, the 6061 Al-HEAp-40 h composite exhibited a heterogeneous grain structure with a multimodal grain size distribution, which was linked to fine HEAp clusters and recrystallisation behaviour. Fig. 7 shows that the changes in the mechanical properties of the three composites are due to the even particle dispersion of HEAps and the heterogeneous grain structure, highlighting the vital role of milling time. As a result, milling time is a key metric to consider when fabricating Al/HEAp composites.

*3.1.1.2. Liquid metallurgy route.* Chitturi *et al.* [61] employed the stir casting method to fabricate a hybrid FeCoCrNiMo and $B_4C$-reinforced Al-based composite. The findings demonstrate that compared to pure 6061 Al, hybrid composite samples exhibit better mechanical characteristics. The composite's mechanical strength improved significantly with a higher volume percentage of FeCoCrNiMo HEAps and a lower volume fraction of $B_4C$. The 6061 Al with the addition of 3 wt% HEAps and 1 wt% $B_4C$ showed the optimum improvement in UTS (29% increment), impact toughness (11.8%) and hardness (25.3%) compared to pure 6061 Al, and the other composites' composition showed lower values than the Al composite reinforced with 3 wt% HEAps and 1 wt% $B_4C$.

Nano-crystalline HEAps have exceptional thermal stability, hardness and stiffness [100]. This is because a significant portion of the grain boundaries of nano-crystalline particles are not in a state of equilibrium, and the properties will change due to grain growth during processing [100]. Lu *et al.* [102] produced $CoNiFeAl_{0.4}Ti_{0.6}Cr_{0.5}$ HEAps via mechanical alloying, and the composites were fabricated using the squeeze casting method. A hybrid composition of 7075 Al/HEAp (5 wt% HEAp + 40 wt% SiC) and single-phase reinforced 7075 Al/SiC (45 wt% SiC) composites were produced. The 7075 Al/HEAp composite, as opposed to the 7075 Al/SiC composite, has more strength, higher Youngs modulus and excellent plasticity on average, with values of 712 MPa, 171 GPa and 0.82%, respectively. The improvement was ascribed to the high-strength nano-crystalline HEAps used as the reinforcement, excellent dislocation density in the Al matrix and the improved particle-matrix interface. Li *et al.* [15] investigated the effects of AlFeNiCrCoTi HEAps on the microstructural and mechanical strength

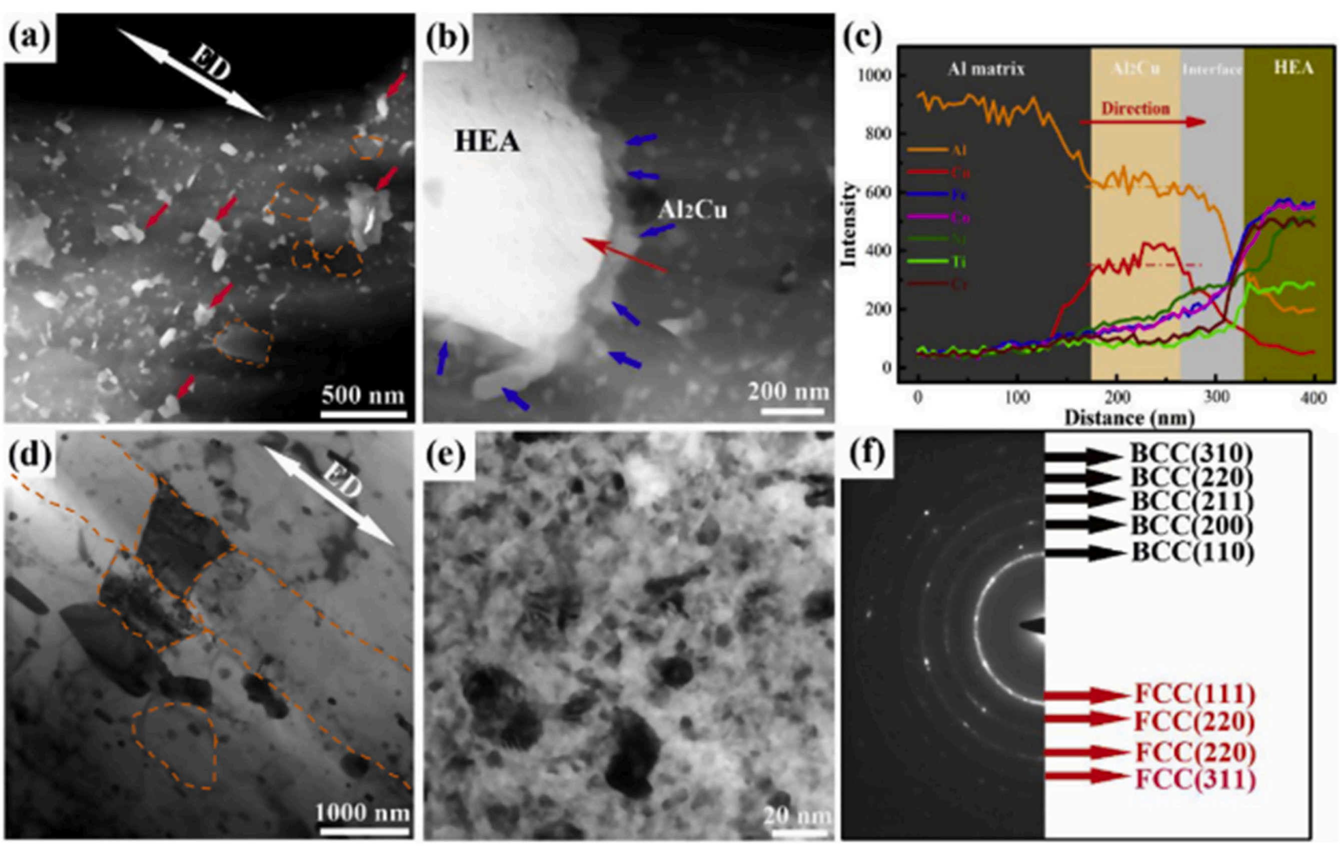


**Fig. 6.** (a) Dark-field transmission electron microscopy (TEM) image of the 7.5HEA-2024 Al sample, (b) the high entropy alloy particle (HEAp)/2024 Al interface in the 7.5HEA-2024 Al sample, (c) linear scanning of HEAp/2024 Al interface in (b), (d) the bright-field TEM image of the 2024 Al sample, (e) the grains of nano-crystalline-HEAps in the composite, (f) the selected area diffraction pattern corresponding to (e).
[100] culled with permission from Elsevier.

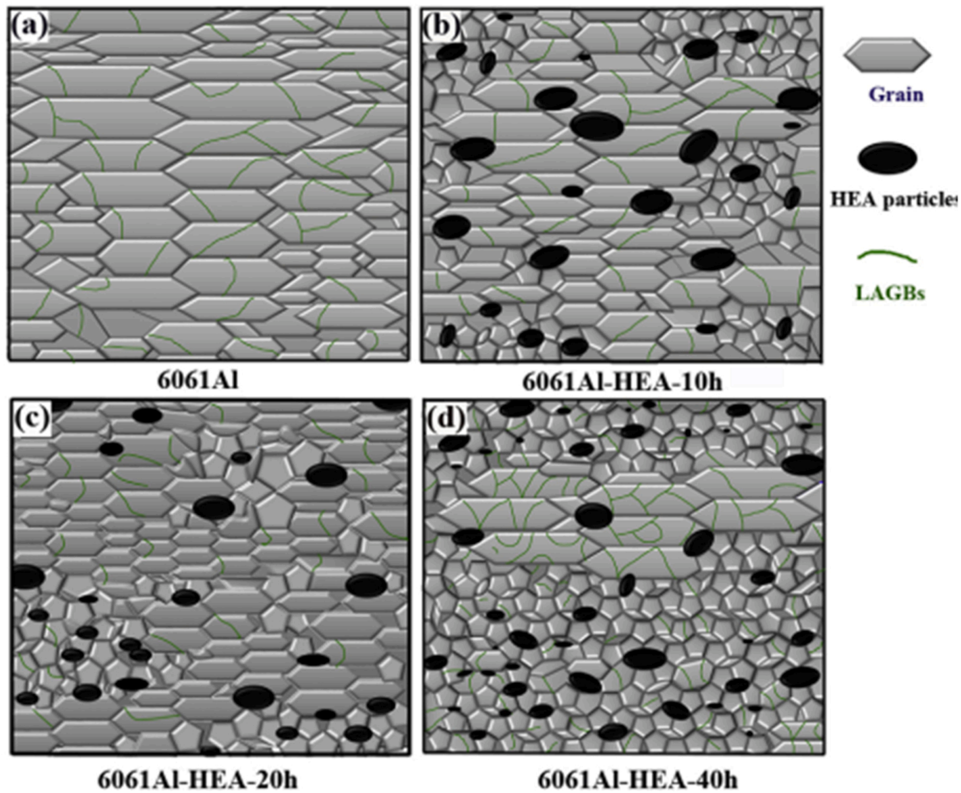


**Fig. 7.** Schematic diagram of grain characteristics in 6061 Al, 6061 Al-HEAp-10 h composite, 6061 Al-HEAp-20 h composite and 6061 Al-HEAp-40 h composite (HEA – high entropy alloy; LAGBs – low-angle grain boundaries).
[101]culled with permission from Elsevier.

characteristics of the Al/HEAp composites. The unreinforced Al was significantly refined with the increasing addition of the HEAps (4 to 6 vol% HEAps) as the size of its equiaxed coarse grain structure significantly decreased and formed flaky $Al_3Ti$ and block Al-Ti-Cr intermetallic second-phase interdendrites of α-Al. The UTS and hardness significantly increased as the HEAp content increased but a marginal reduction was observed when incorporating 6 vol% HEAps. The intermetallic phases improved the strength through the solid-solution strengthening mechanism together with grain refinement. The optimum strength-ductility ratio for this composite was obtained at 5 vol% HEAps addition with ultimate tensile strength of 170 MPa and percentage elongation of 22.7%. The percentage elongation showed a constant decrease with all the HEAp additions compared to the unreinforced Al alloy, which was ascribed to the increase in volume fraction of these intermetallic phases. However, the decreased in ductility is still within the adequate ductility range. The composite fracture morphology was characterised with dimples but the number of dimples reduced with increasing HEAps content, indicating that the composite had fractured in a ductile manner, features which are very rare in conventional MMCs.

*3.1.1.3. Friction stir processing.* To mitigate the challenge of interfacial disparity between the Al matrix phase and the reinforcements and to obtain a significant fraction of refined grains within the composite produced with marginal effects on the elongation, some researchers have employed some novel fabrication methods, extensively aiding in understanding the influence of HEAps' capacity to modify the Al matrix properties to fit the different desired service applications. Li *et al.* [18] fabricated a novel Al-based composite reinforced with $Al_{0.8}CoCrFeNi$ HEAps via multi-pass friction stir processing. The particle-stimulated nucleation process reduced the average grain size of the friction stir processed Al/HEAp composites from 4.6 μm Al matrix to 2.8 μm. The friction stir processed Al/HEAp composites' yield strength, UTS and percentage elongation are 200 MPa, 371 MPa and 18.8%, respectively, which are approximately 56%, 42% and 22% significant improvements compared to the friction stir processed Al alloys (141 MPa, 305 MPa and 24.3%) and showing no obvious decrease in elongation. Interfacial diffusion took place, and the constituent at the interfacial zone was shown to be Al3CoCrFeNi instead of intermetallic phases, which is advantageous for successful interfacial bonding.

Even with good properties achieved with friction stir processing, there are still problems in obtaining a homogeneous dispersion of the reinforcement phase within the composite; therefore, multi-pass friction stir processing is usually needed to aid the uniform distribution of the reinforcement within the matrix of the composite [58,103]. In the friction stir processing, heat input will inevitably increase, causing an adverse interfacial interaction between the metallic HEAps and the Al matrix phase. Various methods have been developed to eliminate or weaken the interfacial reaction between the reinforcements and the matrix. Yang *et al.* [76] showed a significant improvement in the micro-hardness and elastic modulus when AlCoCrFeNi HEAps were integrated into the 5083 Al matrix fabricated via underwater friction stir processing. According to the authors, adding HEAps can efficiently speed up dynamic recrystallisation and produce a greater percentage of high-angle grain boundaries due to the particle-stimulated nucleation process (Fig. 8).

Again, in a similar study, using a novel submerged friction stir processing method, Yang *et al.* [58] found that the 5083 Al/HEAp interface displays a two-layer structure, with FCC þ T-phases in the layer closest to the HEAps and another layer of Cr-depleted AlCoCrFeNi HEAps. Compared to the unreinforced matrix, the composites had an approximate 25.1% increment in yield strength and a 31.9% increment in UTS while maintaining an acceptably adequate ductility (18.9%). Fig. 9 shows that the Al/HEAp composite fractured in a ductile manner characterised by hollow dimples and shear zones. When compared with an

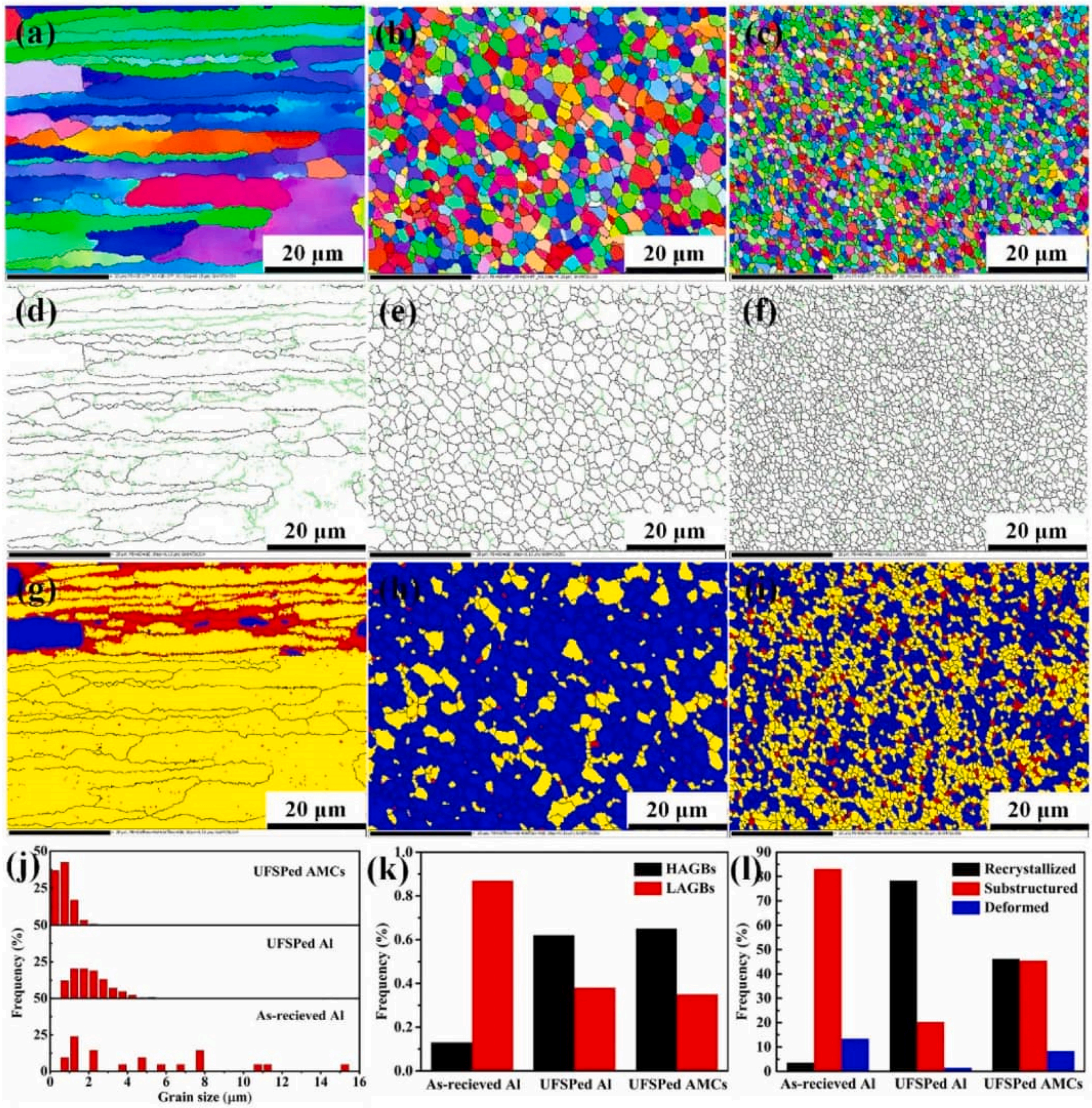


**Fig. 8.** Electron backscatter diffraction results of the as-received Al, underwater friction stir processed (UFSPed) Al, and UFSPed Al matrix composites (AMCs) showing (a, b, c) the inverse pole figures, (d, e, f) microstructures, (g, h, i) recrystallisation maps, respectively, (j) grain size distribution, (k) summarised results of high-angle grain boundaries (HAGBs) and low-angle grain boundaries (LAGBs), (l) summarised results of recrystallised, substructured and deformed region. [76] culled with permission from Elsevier.

Al-based matrix, the friction stir processed Al5083 Al fractured surface exhibits more small-sized dimples with homogenous distribution, suggesting greater elongation.

HEA particles, being inherently more tougher and ductile compared to ceramic systems, provide increased resistance to crack propagation. Their greater capacity for yielding and deformability enables crack tip blunting, thereby mitigating potential stress intensification levels ahead of crack tip near the matrix/particle interfaces. In contrast to ceramics, which exhibit inherent brittleness, particle cracking, pull-out, interface cracking, or particle decohesion can generate stress conditions conducive to rapid crack propagation and brittle fracture. [11,27,28] These conditions, conducive to swift crack propagation, are commonly observed in metal matrix composites reinforced with hard and brittle materials. This is a common fracture micro-mechanism observed in metal matrix composites (MMCs) reinforced with ceramic materials. This conclusion is substantiated by the examination of fractographs from Al/HEAps composites, which exhibit a greater presence of dimple features, indicative of ductile fracture, compared to composites based on aluminum reinforced with ceramic systems.[15,58,100].

*3.1.1.4. Influence of heat treatment.* Yuan *et al.* [73] investigated the influence of heat treatment on the interfacial reactions of the vacuum

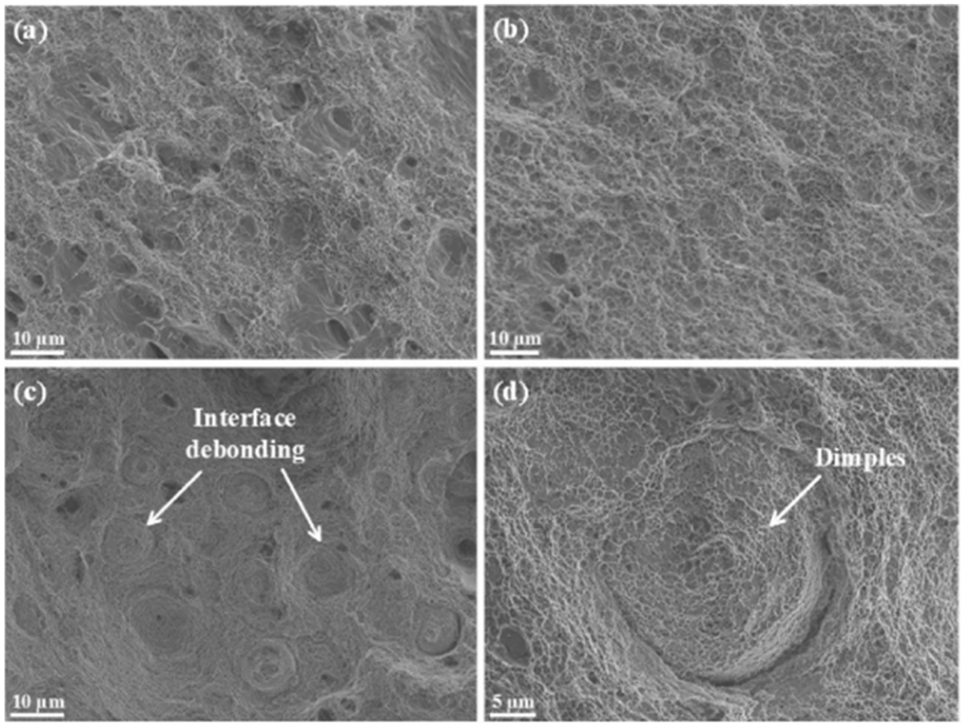


**Fig. 9.** Fracture surfaces of (a) Al-based matrix, (b) submerged friction stir processed 5083 Al, (c) and (d) submerged friction stir processed HEAp/5083 Al composites.
[58] culled with permission from Elsevier.

hot pressing sintered 5052 Al-based composite reinforced with $Al_{0.6}CoCrFeNi$ HEAps to investigate how this treatment influences the mechanical properties of the sintered composites. Yuan *et al.* [73] concluded that there was an observed increment in the thickness of the interface layer as the heat treatment duration increases, and the discontinuous interface layer enhanced the composites' hardness and Youngs modulus, which are related to the stress concentration and the level of bonding at the matrix-reinforcement interface. The X-ray diffraction patterns of the composites at various heat treatment time intervals and temperatures are shown in Fig. 10. It is clear that no new phases are produced during heat treatment, and the Al (Co, Fe) and $Al_{12}Mg_{17}$ phases' diffraction peaks increase marginally. The location of the diffraction peaks also moves at distinct amplitudes as the heat treatment duration and temperature rise. This might be due to the diffusion of the HEAps into the Al matrix during heat treatment, eventually resulting in lattice distortion.

In another study, Li et al. [105] used friction stir processing to produce new 6061-T6 AMCs reinforced with $AlCoCrFeNi_{2.1}$ HEAps, and the resulting composites were strengthened further by T6 heat treatment. They investigated how reinforcement phase variation affected the microstructure and mechanical characteristics of the composites. In contrast to using pure metal particles as reinforcements, AlCoCrFeNi2.1 HEAp is an efficient reinforcement material for strengthening the Al matrix. It successfully inhibited the development and growth of intermetallic phases. The composites' recrystallisation degree rose while the grain size reduced as the amount of HEAps in the resulting composites increased (Fig. 11). The continuous and dense contact zone demonstrates strong metallurgical interface bonding between the Al alloy and the reinforcement (HEAps). No intermetallic compounds were generated at the interface because of the low processing temperature of friction stir

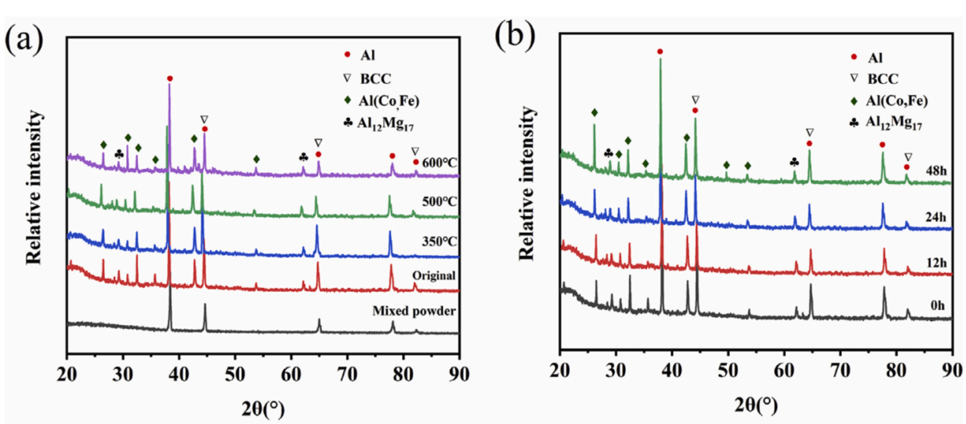


**Fig. 10.** X-ray diffraction patterns of composites under different heat treatment conditions show (a) heat treatment at different temperatures at 24 h; (b) heat treatment at 500℃ at different times.
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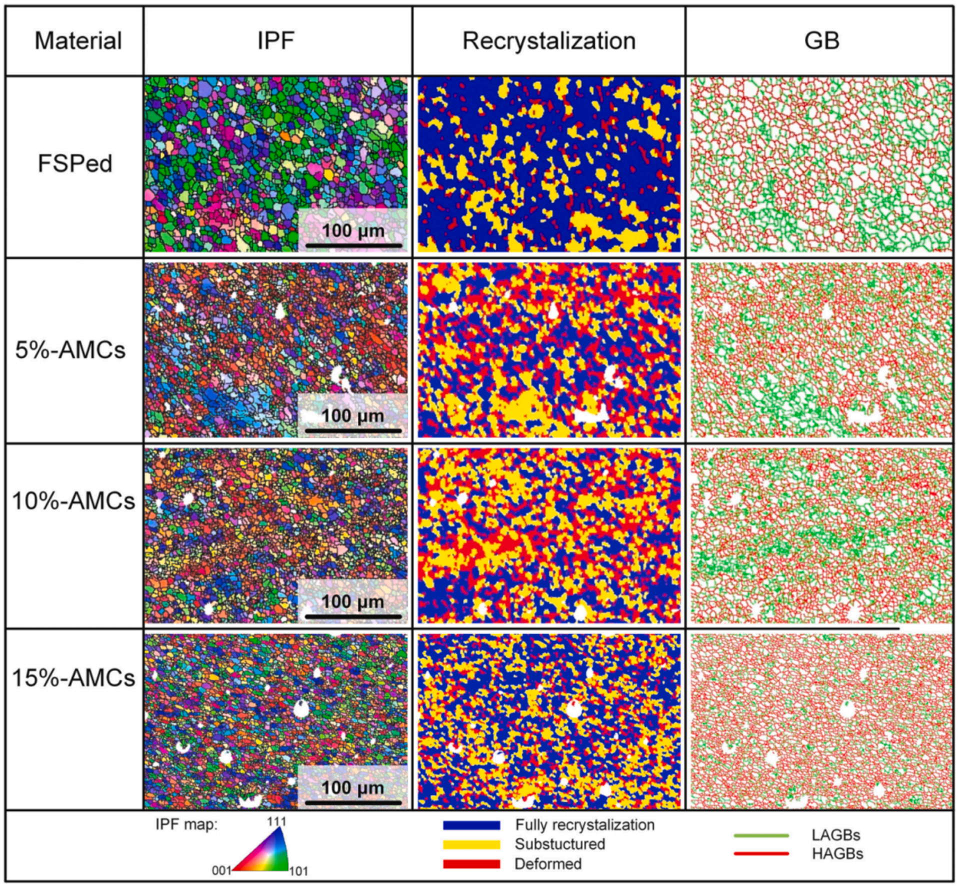


**Fig. 11.** Electron backscatter diffraction results of composites with different volume fractions (FSPed – underwater friction stir processed; GB – grain boundaries; HAGBs – high-angle grain boundaries; IPF – xxx; LAGBs – low-angle grain boundaries).
[105] culled with permission from Elsevier.

processing, which successfully prevented the dramatic chemical reaction. The reinforcing content increased the composites' tensile strength and hardness. The composites with 15% HEAps had enhanced tensile strength and hardness by 25.6% and 28.6%, respectively, compared to friction stir processed 6061 Al. The strength improved significantly after the ageing heat treatment of the $AlCoCrFeNi_{2.1}$-reinforced 6061-T6 AMCs. In addition, the composite's hardness and tensile strength increased by 73.6% and 49.0%, respectively, demonstrating that Hall-Petch and thermal mismatch strengthening mechanisms had a substantial beneficial impact on strengthening, whereas Orowan strengthening had the least impact.

Recently, deep cryogenic treatment has been explored by some researchers to investigate the influence of cryogenic conditions on the mechanical strength of the novel Al/HEAp composites. Liu *et al.* [106] investigated the influence of deep cryogenic treatment on the mechanical characteristics and microstructural evolution in Al/(FeCoNi1.5CrCu) HEAp composites. The outcomes showed that the (111) and (200) crystal face indexes changed to (220) by internal tension that was generated during deep cryogenic treatment. Preference orientation is crucial to promote plasticity. The macro performance demonstrates the transition of the fractures from one-way to two-way crack propagation, and the multi-system slip caused a 155.6% increment in the deep cryogenic treated sample's fracture toughness compared to the control (untreated) sample.

In summary, these studies have shown ways to get a good balance of mechanical properties. Significant improvements in the UTS, hardness property and yield strength were observed in the Al/HEAp composites. Also, these studies covered the influences of the production processes on mechanical properties. Friction stir processing improved grain refinement showing a clear improvement in the hardness property and UTS, as well as the yield strength of the AMCs. However, the processes' heat input caused the emergence of detrimental phases within the composites. Underwater and submerged friction stir processing methods were established to be the right solutions to this problem. Still, not many studies tackle the problem faced using the friction stir processing method. From the literature, conventional powder metallurgy and spark plasma sintering also considerably improved the AMCs' properties and helped to achieve a good balance of properties. The review considered a few publications on the effect of heat treatment methods to improve the process. This area needs considerable attention; from the reviewed studies, we concluded that these treatments significantly improved the mechanical properties.

It is also worth mentioning that most of the considered publications compared their findings with monolithic alloys; there is currently little or no information on the influence of hybrid reinforcement on the general mechanical properties of AMCs. Additionally, most of the articles on HEAp-reinforced Al-based composites (summarised in Table 4) compared the mechanical properties obtained with unreinforced alloy rather than conventional ceramic-reinforced AMCs; thus, additional research should be conducted to determine how much the mechanical properties (including ductility and toughness) are improved when comparing Al/HEAp composites to conventional ceramic-reinforced AMCs. This will serve as the cornerstone for defining optimal processing parameters in relation to production costs.

### 3.1.2. Copper matrix

Cu matrix composites are now the most sought-after material of choice for various technological applications that call for increased heat

**Table 4**
Mechanical properties of selected high entropy alloy particle (HEAp)-reinforced aluminium matrix composites (AMCs) and the effect of fabrication techniques.

| Reference | Aluminium matrix | HEAp reinforcement | Fabrication process | Samples | Particle content (wt%) | Hardness | Tensile strength (MPa) | Yield strength (MPa) | Percent elongation |
|---|---|---|---|---|---|---|---|---|---|
| [96] | AA7075 | $Fe_{1.2}NiCrCoAlTi_{0.8}$ | Powder metallurgy | At: | 10 | 182.13HV | 508.5 | – | 5.23 |
| | | | | 20 MPa/ | 5 | 141.75HV | 510.13 | | 12.34 |
| | | | | 300° C | 15 | 173.50HV | 582.13 | | 10.99 |
| | | | | 20 MPa/ | 5 | 157.38HV | 530.63 | | 6.96 |
| | | | | 450° C | 15 | 186.63HV | 680.63 | | 6.11 |
| | | | | 60 MPa/ | 10 | 182.13HV | 694.50 | | 5.23 |
| | | | | 600° C | | | | | |
| | | | | 100 MPa/ | | | | | |
| | | | | 600°C | | | | | |
| [105] | 6061 Al | AlCoCrFeNi | Friction stir processing + T6 heat treatment | – | 0 | 56 HV | 309.3 | – | 13.2 |
| | | | | | 5 | 60 HV | 177.5 | | 20.3 |
| | | | | | 10 | 67 HV | 192.1 | | 16.7 |
| | | | | | 15 | 72 HV | 222.9 | | 19.3 |
| | | | | | 15 + T6 | 92 HV | 332.1. | | 14.5 |
| [76] | 5083 Al | AlCoCrFeNi | Spark plasma sintering | – | 0 | – | 178 | 101 | 4.7 |
| | | | | | 5 | | 144 | 113 | 2.0 |
| | | | | | 10 | | 153 | 121 | 1.8 |
| | | | | | 15 | | 141 | 131 | 0.7 |
| [106] | 2024 Al | $FeCoNi_{1.5}CrCu$ | Powder metallurgy + solution treatment and deep cryogenic treatment | – | 150 | | 394.96 | – | 4.45 |
| | | | | | 160 | | 399.78 | | 6.95 |
| | | | | | 170 | | 408.78 | | 6.26 |
| | | | | | | | 383.56 | | 6.81 |
| [54] | 2024 Al | CoCrFeMnNi | Spark plasma sintering | – | – | 131.20HV | – | – | – |
| | | | | | | 127.78HV | | | |
| | | | | | | 135.48HV | | | |
| [58] | 5083 Al | AlCoCrFeNi | Submerged friction stir processing | – | 5083 Al SFSPed | – | 304 | 178 | 22.6 |
| | | | | | 5083 Al SFSPed | | 327 | 184 | 25.6 |
| | | | | | HEAp/5083 Al | | 401 | 219 | 18.9 |
| [93] | | AlCoCrCuFe | Powder metallurgy | | 0 | 37.6HV | | | |
| | | | | | 15 | 71.3HV | | | |
| [107] | 6061 Al | FeCoNi $(AlSi)_{0.5}$ + $B_4C$ | Stir casting | S1 | $1B_4C$+ 0. 2HEA | 107BHN | | | |
| | | | | S2 | $2B_4C$+ 0. 4HEA | 103BHN | 268 | | |
| | | | | S3 | $3B_4C$+ 0.6HEA | 109.5BHN | | | |
| [61] | 6061 Al | FeCoCrNiMo + $B_4C$ | Stir casting | 6061 Al | Pure 6061 Al | 30HV | 96.922 | – | 15.230 |
| | | | | S1 | 6061 Al+ 1HEA+ 3 $B_4C$ | 32.4HV | 100.690 | | 17.890 |
| | | | | S2 | 6061 Al+ 2HEA+ 2 $B_4C$ | 33.8HV | 115.005 | | 20.340 |
| | | | | S3 | 6061 A+ 3HEA+ 1 $B_4C$ | 37.6HV | 125.190 | | 22.880 |
| [99] | | CuZrNiAlTiW | Spark plasma sintering | Pure Al | 0 | 34HV | 98 ± 2 | 39 ± 8 | 15.11 |
| | | | | Al10 | 10 | – | 344 ± 2 | 258 ± 12 | 7.23 |
| | | | | Al20 | 20 | – | 544 ± 2 | – | 6.57 |
| | | | | Al30 | 30 | 331HV | 270 ± 2 | – | 3.09 |
| [18] | AA5083 | $Al_{0.8}CoCrFeNi$ | Friction stir processing | FSPed Al alloy | | 125.7 HV | 141.2 ± 1.8 | 141.2 ± 1.8 | 24.3 ± 0.7 |
| | | | | FSPed AMC | | 80.5 HV | 200.5 ± 2.7 | 200.5 ± 2.7 | 18.8 ± 0.5 |
| [15] | | AlFeNiCrCoTi | Stir casting | | 0 | 26.4HV | 58 | – | 40 |
| | | | | | 4 | 48.8HV | 142 | | 26.6 |
| | | | | | 5 | 55.6HV | 170 | | 22.7 |
| | | | | | 6 | 75.2HV | 157 | | 18.2 |
| [97] | 7075 Al | AlCrTiV | Powder metallurgy | Al | 0 | – | 57.8 | 30.6 | 49.1 |
| | | | | Al-3 wt% HEAp | 3 | | 89.2 | 42.5 | 46.8 |
| | | | | Al-6 wt% HEAp | 6 | | 104.7 | 49.8 | 18.7 |

resistance and exceptional microstructural integrity. [37,108] Cu matrix reinforced with ceramic particles such as TiC, $Al_2O_3$, SiC and $Cr_2O_3$ has been extensively studied. [109,110] This set of composites achieved good results in terms of strength but still has limitations, such as poor ductility due to the high differential coefficient of thermal expansion between the matrix and the reinforcing particles [111]. Poor wettability and interface reactions have also been reported as part of the system's demerits. [112] Concerted efforts over the years to surmount this problem include the integration of an amorphous phase in the Cu matrix composites, but this approach is marred by resultant poor mechanical properties at elevated temperatures due to the low crystallisation temperature of the amorphous phase and its low fracture toughness. [113] To match the demand of modern technology, more effort is being made to shift reinforcing materials from conventional ceramics and metals to special alloys such as HEAs to meet the stringent requirements. [114].

*3.1.2.1. Powder metallurgy route.* Yu *et al.* [37] investigated Cu matrix composites reinforced with $Al_{0.3}CoCrFeNi$ HEAPs produced via mechanical alloying followed by sintering. Ball milling was used in multiple steps to create the transition layer structure, which was then used to analyse how element diffusion behaviours and Cu matrix composites' mechanical and wear characteristics were affected. The research shows that the solution-hardening effects of Fe, Ni and Co in the matrix enhanced the hardness property of the Cu-based composite, causing it to be more resistant to deformation than monolithic Cu. In research by Liu *et al.*, [108] Cu matrix composites reinforced with 10 wt% HEAps were produced utilising spark plasma sintering at different soaking durations and a sintering temperature of 850 °C. This was followed by hot extrusion to enhance the performance of HEAps as a reinforcement phase in the sintered Cu-based composites. The findings show that the core-shell structure becomes undetectable as the preheating duration exceeds six hours. The properties' enhancement observed in the Cu-based composites' yield strength at less than six hours holding time was linked to the solid-solution strengthening of the Cu matrix resulting from the diffusion of the elements from the HEAps to the Cu matrix, while the enhanced plasticity is caused by the reinforcements' increasing shell thickness with preheating time. Over six hours, the reinforcements' strengthening impact significantly diminishes, leading to a decline in yield strength and an increase in plasticity. The heat-treated Cu/HEAp composites for two, four and six hours enhance their yield strength by 30%, 35% and 92%, respectively. This suggests that the mechanical strength of the 10 wt% HEAp/Cu composites can be enhanced effectively with a suitable preheating duration. The mechanical characteristics of Cu-based composites reinforced with 10 wt% HEAp after being heated for various lengths of time are shown in Fig. 12. The Cu-based composites reinforced with 10 wt% HEAps may not have a high work-hardening rate, according to Fig. 11(b).

*3.1.2.2. Friction stir processing.* The effects of Al-Co-Cr-Cu-Fe HEAps on the mechanical characteristics of the Cu matrix composites produced via friction stir processing were investigated by Seenivasan *et al.* [115] The results show that every increase in the HEAp vol% results in enhanced mechanical strength compared to unreinforced Cu. This kind of strength improvement with HEAp additions can very likely be attributed to HEAps' resistance to grain growth, which leads to smaller grains. Among the examined Cu composites (5%, 10% and 15 vol% HEAps), samples containing 15 wt% HEAps yielded an optimistic assessment (higher strength and hardness, as well as low wear rate). Also, it is clear from the test results that Cu becomes more brittle when the reinforcement phase (HEAps) percentage is raised, meaning that the elongation percentage drops.

Zhu *et al.* [41] examined the microstructure, as well as the mechanical characteristics, of Cu-based composites manufactured using friction stir processing. The composites were reinforced with FeCoNiCrAl HEAps. Their findings show that the friction stir processing procedure, as well as the incorporation of HEAps, had a role in refining the Cu matrix grains. The Cu matrix's micro-hardness in the composites increased by 69.8%. The remarkable improvement in the hardness property of friction stir processed Cu/HEAp composites was attributed to several variables, including the Orowan process caused by the HEAps and the Hall-Petch strengthening mechanism caused by the Cu matrix's finer grain structure. Particle-stimulated nucleation(PSN)-induced recrystallization is accelerated at the interface due to the large differences in the elastic modulus and thermal expansion coefficients between HEAps and the Cu matrix. As a result, there is significant reduction in grain size in the vicinity of the HEAps/Cu interface. The UTS of the friction stir processed Cu/HEAp composite was greater than that of friction stir processed Cu/HEAp composite. The composite layer's strength was much greater than that of the matrix material. Comparing the as-received Cu and friction stir processed Cu/HEAp composite, both with an elongation of 30.66%, the friction stir processed composite had one substantially higher at 47.34%. This was primarily ascribed to an increase in high-angle grain boundaries within the matrix during production, which made it simpler to enhance the grain boundary slip mechanism during plastic deformation.

It can be inferred from the reviewed articles that HEAp reinforcement is promising, and heat treatment can enhance the composite's strength and ductility. HEAp reinforcement greatly improved the composite's strength with a marginal reduction in ductility. It is noted that HEAp reinforcement increased copper mechanical properties; however, most of the considered publications compared their findings with monolithic alloys. There is currently little or no information on the strength and hardness compared with ceramics-reinforced Cu-based composites. Hence, additional research should be conducted to determine how much the mechanical properties (including ductility and toughness) are improved when comparing Cu/HEAp composites to conventional ceramic-reinforced Cu-based composites. Future research should focus on using other production techniques, such as stir casting and additive manufacturing processing.

*3.1.3. Magnesium matrix*

The quest to save costs using lower energy-consumption materials has drawn attention to lightweight materials. [116] Mg-based alloys are considered viable and lightweight materials in the automotive and biomaterial industries, sporting goods, defence and aerospace due to their low density and high mechanical strength, as well as excellent physical characteristics. [117] Unfortunately, these Mg-based alloys have poor load-bearing capacity and low elastic modulus. [67] Research targeted towards developing high-performance Mg alloys that will satisfy the extended industrial applications has been triggered. [118] One major progress reported in literature is the consideration of HEAs as reinforcing materials in these Mg-based alloys to take advantage of

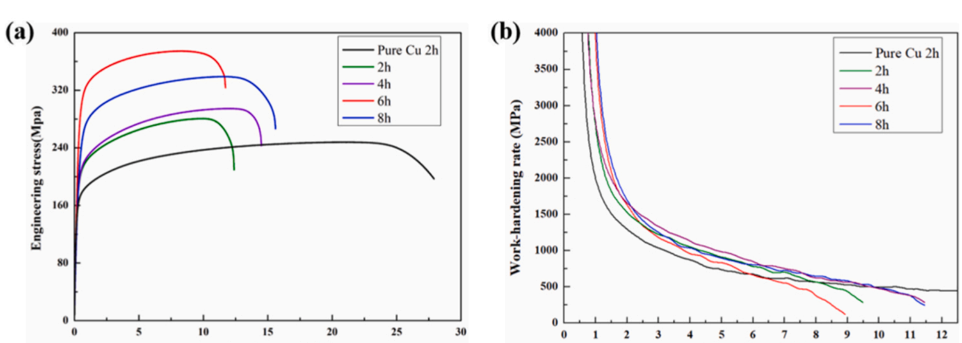


**Fig. 12.** Mechanical properties of 10 vol% high entropy alloy particle/Cu composites as-extruded under various heating times (a) tensile strain-stress curves and (b) work-hardening-strains.
[108] culled with permission from Elsevier

HAEs' lightweight and good characteristics, including good wettability at the matrix/reinforcement interface. [67,119] Further improvement in properties such as strength and ductility of HEAp-reinforced Mg-based composites can be achieved using nano-length scale reinforcing materials. [120].

*3.1.3.1. Powder metallurgy route.* Chiu and Chang [67] investigated using $Al_{0.5}CoCrFeNi_2$ HEAps as reinforcement to develop Mg-based composites via the powder metallurgy route using a spark plasma sintering machine. They demonstrated that AZ91-HEAps' hardness property and compressive yield strength increased substantially when incorporating HEAps. The hardness and compressive yield strength of the composite rose by 48% and 17%, respectively, with the addition of HEAps, and a higher percentage elongation was observed when compared to the unreinforced alloy. The cumulative effects of thermal mismatch, grain refinement and load transfer contributed to the increase in compressive yield strength of the AZ91/HEAp composites. The temperature mismatch effect was the main contributor among them. The compressive yield strength of the Mg/HEAp composites was somewhat greater (209 MPa) than that of the Mg/SiC (204 MPa). Also, the Mg/HEAp composite has a better percentage elongation than the Mg/SiC composite and the unreinforced alloy. HEAp has a similar strengthening effect as conventional SiC reinforcement commonly employed in fabricating MMCs. This occurs due to the reduction in porosity, as well as an increase in the interfacial bonding strength, that exists between the α-Mg matrix phase and the HEAp reinforcement phase. The results of a related study by Huang *et al.*, [121] who successfully prepared AZ91D Mg reinforced with $Al_{0.5}CoCrCuFeNi$ HEAps, reveal that the composite was made up of a basic FCC solid-solution phase. The micro-hardness result that was obtained for this composite was approximately 3.7 times higher than was obtained for the Mg matrix, and it was even higher than what was obtained for the composite with the same HEAp content that was fabricated by arc melting. The research by Tun and Gupta [84] describes an effective method of using equiatomic HEAps as a reinforcing phase in fabricating Mg-based composites. The Mg/HEAp composites were produced via the powder metallurgy route that included hot extrusion and microwave sintering. Due to the potential of HEAps to act as grain boundary pinning after extrusion and as nucleation sites, recrystallised small grains (50% decrease) were seen in all composites. The hardness of composites containing Mg/2.5 wt% HEAps, Mg/5 wt% HEAps and Mg/7.5 wt% HEAps increased by 47%, 51% and 54%, respectively, due to grain refinement and the intrinsically high hardness of HEAps. Mg-HEAp composites showed excellent hardness enhancement compared to conventional micron-size reinforced composites. Moreover, HEAp reinforcement increased the tensile and compressive strengths of Mg while only slightly impairing the tensile ductility and slightly enhancing the compressive ductility. The following mechanisms explain this: a) load transmission caused by micron-sized particles (average size: $1.5 \pm 0.8$ mm); b) Orowan strengthening brought on by several particles in the submicron zone; and c) grain refinement caused by micron-sized particles (>1 mm) (particle strengthening nucleation). Fig. 13 displays the compressive and tensile stress-strain curves of the Mg and Mg/HEAp composites.

It can be inferred from the reviewed articles that HEAp reinforcement is promising and can replace conventional ceramic systems in Mg-based composites. HEAp reinforcement increased the mechanical properties of Mg without deleterious affecting its ductility. Also, most of the considered publications compared their findings with monolithic alloys; there is currently little or no information about the influence of hybrid reinforcement on the general mechanical properties of Mg-based composites. Hence, additional research should be conducted to determine how much the mechanical properties (including ductility and toughness) are improved when comparing Mg/HEAp composites to conventional ceramic-reinforced Mg-based composites. Future research should focus on using other production techniques, such as friction stir

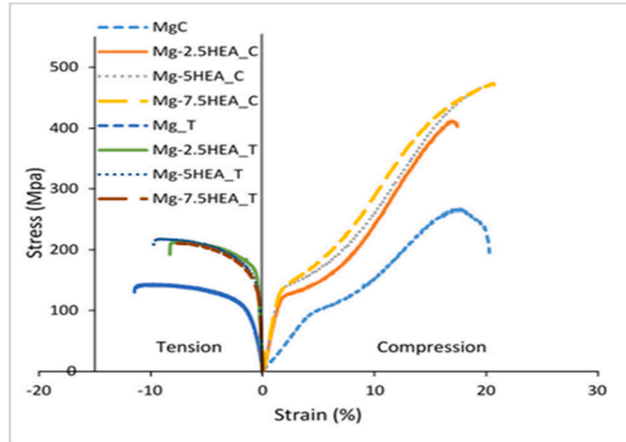


**Fig. 13.** Stress-strain graphs of Mg and Mg-HEAp composites under tensile and compression strain.
[84]culled with permission from Elsevier.

processing and additive manufacturing.

### *3.1.4. Titanium matrix*

Ti-based composites are attractive for technical applications due to their high stiffness, strength and wear resistance. Ti alloys have improved materials property in terms of strength. [122,123] Ceramic-based materials have been used as reinforcing materials in Ti-based composites to enhance their overall strength. Good results have been recorded with some limitations as well. [124] One such limitation is the poor interface bonding between the reinforcements and Ti matrix due to poor wetting characteristics, which reduce the workability of the materials. [125] The second problem is the poor fluidity of the ceramic reinforcing materials in Ti matrix composites. [31,125,126] Using the metal/metal composite system has been projected to proffer a solution to the problem due to their good interface bonding characteristics.[106] Zr, Al and Mg-based alloys are used as reinforcement in their amorphous state to strengthen MMCs. These amorphous alloys are brittle and have low crystallisation temperatures, making it difficult to process them during sintering processes. [31] HEAs have complex concentrated solid solutions of a wide range of principal elements, making them superior to traditional alloys in terms of mechanical properties. [127–129] Also, HEAs exhibit many interesting properties, including high strength, exceptional wear resistance and outstanding thermal stability. In particular, HEAs have higher ductility than ceramics and amorphous alloys. [65].

*3.1.4.1. Powder metallurgy route.* Xiong *et al.* [65] induced repeated strengthening by incorporating HEAps in Ti matrix composites fabricated by spark plasma sintering. Their findings show that all composites had greater yield strengths and hardness properties when adding HEAs than the unreinforced Ti-6Al-4 V. The disparity in the coefficient of thermal expansion between the Ti matrix and the HEAp reinforcement was thought to be responsible for the increase in hardness observed in the sintered composite after it had been processed. According to the authors, by incorporating HEAps, the likelihood of lattice distortion of the base alloy increases, grain refining occurs and grain boundaries emerge, inhibiting dislocation slip, all of which contribute to improving the sintered composites' hardness. The sintered composite, which has 4.5 vol% of HEAps added as reinforcement, produces a remarkable elongation to failure under a tension of 8.8% and a significant UTS of 1150 MPa. The enhanced strength results were ascribed to a combination of various strengthening mechanisms, including load transfer strengthening, dislocation strengthening and grain refinement strengthening. Yuan *et al.* [85] employed vacuum hot pressing sintering to fabricate Ti/HEAp composites. The sintered composites' mechanical and microstructural characteristics were investigated. At temperatures between 700 and 850 °C, there was an increase in the mechanical properties. These increased mechanical properties of the composites are linked to both the diffusion of HEAps, as well as the growth of the interface layer. At 850 °C during sintering, the material has a yield strength of 928.2 MPa, a hardness of 402.6 HV and a compressive strength of 2032.6 MPa. This can be explained by fine grain strengthening, load transfer, Orowan strengthening, solid-solution strengthening, and the emergence of a tough diffusion layer between the HEAps and the Ti matrix, which considerably enhanced the composites' mechanical characteristics with a core-shell structure. However, the strengthening impact of the HEAp reinforcement particles is less at 900 °C because of a higher level of dissolution and dispersion. In a study by Satyanarayanaraju *et al.*, [64] Ti-based composites reinforced with $Al_{0.5}Si_{0.5}FeCoNi$ HEAps were fabricated via powder metallurgy and uniaxial compaction at 1000 MPa. They investigated how heat treatment affected the microstructure and properties of the HEAp-reinforced Ti-based composites. The vol% increase in HEAps caused the pure titanium's hardness to rise from 280 to 700 VHN. Although the hardness of the composites increased with heat treatment temperatures, the samples heat treated at 900 °C showed a significant improvement in mechanical strength compared to those heat treated at other temperatures. The scanning electron micrograph of the heat-treated composites over 900 °C revealed that there may be diffusion at the Ti-HEAp interface. The scanning electron micrographs of heat-treated composites (25 wt% HEAps) at different temperatures are displayed in Fig. 14.

Notably, the studies reviewed in this section only considered powder metallurgy production techniques, and there is no comparison between elongation and HEAp reinforcements. The highlighted strength metrics were not compared with conventional Ti composites with ceramic reinforcements. Future research should focus on using other production techniques, such as friction stir processing and additive manufacturing, and should provide a critical comparison via the production of hybrid Ti-based composites using HEAps and conventional ceramic reinforcements.

### 3.1.5. *Tungsten matrix*

WHAs are widely employed in ballistic applications relating to plasma-facing components, [130] aircraft counterbalances, radiation shields, ballasts, vibration-damping devices, kinetic energy penetrators and pre-fragments. [131] This is attributed to their excellent mechanical properties, [132], heavy weight, [131] high erosion-resistance and melting point, substantial radiation shielding, excellent thermal conductivity, low sputtering, high structural integrity and endurance limit. [130] Improving these properties, especially in terms of strength and toughness, has been sought to widen their field of applications [133]. Several approaches have been adopted to improve their properties, but incorporating reinforcements is prominent and cost-effective. It has been reported that HEAs with an FCC structure substantially enhance the impact toughness of the brittle W phase [134].

*3.1.5.1. Powder metallurgy route.* Anwer *et al.* [134] examined the mechanical properties and microstructural evolution of WHA reinforced with FeNiCoCrMn HEAps and compared them with conventional WHA with Fe-Ni binders. At 1450 °C in an Ar environment, hot isostatic pressing was employed to produce both WHAs with HEAps and with conventional Fe-Ni binders. The WHAs/HEAp composites' micro Vickers hardness values increased by 42%. Interestingly, adding HEAps during fabrication enhanced the WHA's hardness. Microstructural

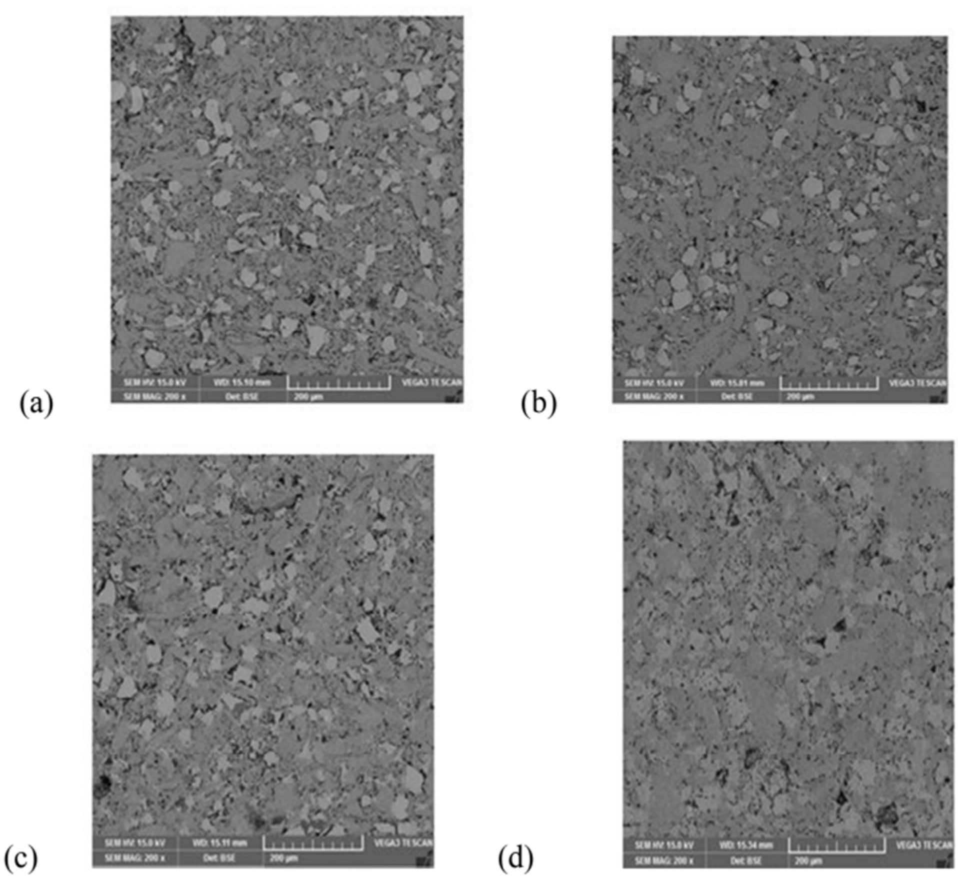

**Fig. 14.** Scanning electron micrographs of metal matrix composite (sample 5) heat treated at (a) 600 °C, (b) 700 °C, (c) 800 °C and (d) 900 °C. [64] culled with permission from Elsevier.

elements that restrict dislocation movement, such as dislocation density, point defects, strain hardening, grain boundaries, stacking faults, reinforcements and micro-scale precipitates, to mention a few, aid in enhancing hardness. A premature failure and faster strain hardening were seen in the HEAp-reinforced WHA sample, resulting in reduced ductility properties. The minor oxide formation during hot isostatic sintering acts as reinforcement and impedes the movement of the dislocations, causing a greater strain hardening effect within the WHA/-HEAp composites. The total strain-to-failure values further support this, showing that porosity within the composite, in addition to oxide areas, significantly contributed to the early failure of the HEAp/WHA samples. Future research should focus on how to eliminate porosity and oxide formation hindering the composite's ductility. There is dearth of publication in this area and more research needs to be done, focusing on using other production techniques such as friction stir processing and additive manufacturing, and should provide a critical comparison via the production of hybrid W-based composites using HEAps and conventional ceramic reinforcements. Furthermore, Table 5 provides a summary of most of the articles on HEAp-reinforced with other metal matrices (i.e. Cu, Mg, Ti, and W). The table compares the mechanical properties of these composites with those of unreinforced alloys, rather than conventional ceramic-reinforced MMCs. Therefore, further research is needed to determine the extent to which the mechanical properties, including ductility and toughness, are enhanced in MMC/HEAp composites compared to conventional ceramic-reinforced MMCs.

### 3.2. Wear resistance

Wear frequently occurs whenever there is any kind of relative motion in any part, such as reciprocating and rotational piston movements, cylinder bores, brake rotors, connecting rods and so on. When manufacturing these kinds of components, wear is an essential factor to consider to guarantee better and more constant performance in any tribological application. The conventional MMCs showed greater wear resistance than their monolithic alloys. However, their poor fracture toughness and low ductility hindered their employment in service applications. HEAs display exceptional physical qualities, such as exceptional strength metrics and hardness, excellent thermal stability, and high levels of wear resistance. As a result, HEAs are potentially very promising materials for enhancing the wear resistance of the metal matrix. We discuss the wear behaviour of HEAp-reinforced metal matrix composites in the succeeding sub-sections.

#### 3.2.1. Aluminium matrix

AMCs exhibit better wear resistance than typical Al alloys, enabling them to withstand difficult braking challenges. The wear behaviour of conventional AMCs reinforced with ceramic particulates has been extensively studied. HEAps have drawn much interest as unique multi-principal element metal alloys because of their excellent wear resistance, which makes them a promising material that can serve as a suitable reinforcement in Al-based composites. [135,136] The fabrication technique has been employed to increase the wear resistance of Al/HEAp composites further. Yang *et al.* [104] conducted a wear test on AlCoCrFeNi HEAp-reinforced A5083 AMCs fabricated via underwater friction stir processing. These Al/HEAp composites had the lowest friction coefficient and wear rate of all the samples, and the composite wear rate was reduced by 48.6% compared to the as-received Al matrix (Fig. 15).

In a related investigation, Zhang *et al.* [136] found that Al/HEAp composites' tribo-systems with a reasonable range of reinforcement proportions (0.5 wt% to 3.0 wt%) had lower coefficients of friction and wear rates than the Al matrix. The composites' wear track under a 30 kN load is shown in Fig. 16. The HEAps prevented plastic deformation of the composites' contact surface, enhancing the composites' wear resistance. In a study by Prakash *et al.*, [93] AlCoCrCuFe HEAps considerably increased the wear resistance of the Al/HEAp composites. As the addition of HEAp reinforcement increased, the wear rate of the Al-based composite decreased drastically.

Li *et al.* [15] established that the wear resistance of the produced AMCs increased due to the hard $Al_3Ti$ and Al-Ti-Cr phases present in the matrix of the Al-Fe-Ni-Cr-Co-Ti HEAp-reinforced Al-based composites. In a similar study, Gao *et al.* [60] investigated how friction stir process fabricated FeCoNiCrAl HEAp-reinforced 5083 Al-based composites' wear characteristics were influenced by the proportion of reinforcing particles, as well as the number of processing pass. The Al/HEAp composites had greater micro-hardness and wear resistance than the 5083-Al base alloy and friction stir processed samples without the Fe-Co-Ni-Cr-Al HEAps.

This review covered some of the few recent studies of Al/HEAp-reinforced composites. Generally, HEAp reinforcement improves the composites' wear resistance and friction coefficient compared to Al alloys. Also, intermetallic compounds significantly impact composite wear. However, more studies focused on the wear properties of Al/HEAp composites are needed, focusing on exploring the effects of different HEAp reinforcement, hybrid AMCs, and different processing techniques and heat treatment methods. The authors of the reviewed studies failed to compare their findings with the wear rate and wear mechanism of conventional Al-based composites with ceramic reinforcement. Also, more work is required to elucidate the wear rate and wear mechanisms of Mg/HEAp composites. This aspect remains an open area of research. Hence, future research should consider this comparison to obtain composites with better wear resistance.

#### 3.2.2. Copper matrix

A recent study established that friction stir processed Cu/HEAp composite exhibits a much greater micro-hardness than as-received Cu and friction stir processed Cu, with an average hardness value of 209.46 HV. Also, the wear rate of novel friction stir processed Cu/HEAp composites was significantly lower than as-received Cu. The obtained wear rate of friction stir processed Cu/HEAp composites was reduced by 29.7% compared to as-received Cu. [41] Stress concentration at the Cu matrix-HEAp interface weakens the properties of Cu matrix composites. [37,114] To ameliorate this challenge, using a transition layer structure (M) has been reported to successfully increase the composites' wettability, interfacial strength and wear resistance [62,137] owing to its single FCC phase and excellent Vickers hardness property. [114] In similar work, Yu *et al.* [37] discovered that HEAp/M/Cu composites had better wear resistance than HEAp/Cu composites. Multi-step ball milling the transition layer structure modifies the diffusion behaviour of the constituents, as well as the wear behaviour due to the fresh and clean interface. The study shows that diffusion behaviour improves the wear resistance of Cu/HEAp composites. Fig. 17 (a) and (b) display scanning electron micrographs of the two composites' wear tracks. Numerous grooves and adhesion phenomena can be seen in the two composites' sign and appearance. Also, Seenivasan *et al.* [115] reported that the coefficient of friction value rose slightly while the Cu/HEAp composites' wear rate values decreased with respect to the increased HEAp reinforcing weight percent. It is very likely that the HEAps' capacity to withstand load contributed to the composite's increased coefficient of friction.

Using HEAps as reinforcement in Cu matrix showed great potential in reducing the wear rate of the Cu matrix. It is worth mentioning that more research needs to be done in this area. Future research should focus on using other production techniques, such as friction stir processing and stir casting, the effects of different HEAp reinforcement, hybrid Cu matrix composites, and different processing techniques and heat treatment methods, and should provide a critical comparison via the production of hybrid Cu-based composites using HEAps and conventional ceramic reinforcements to obtain the composite with optimum wear resistance.

**Table 5**
Mechanical properties of selected high entropy alloy particle (HEAp)–reinforced metal matrix composites (MMCs) and the effect of fabrication techniques.

| Reference | Matrix | HEAp reinforcement | Fabrication process | Samples | Particle content (wt %) | Hardness (HV) | Tensile strength (MPa) | Yield strength (MPa) | Compressive strength (MPa) | Comp. yield strength (MPa) | Percent elongation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [108] | Cu | AlCoCrFeNi | Spark plasma sintering + hot extrusion | Pure Cu | – | 58.7 ± 1.51 | 235 | 163 ± 8 | – | – | 24.6 ± 1.2 |
| | | | | Cu-HEAp-2 h | 10 | 89.5 ± 2.30 | 271 | 212 ± 4 | | | 11.2 ± 0.8 |
| | | | | Cu-HEAp-4 h | 10 | 89.7 ± 3.01 | 285 | 220 ± 4 | | | 14.2 ± 0.2 |
| | | | | Cu-HEAp-6 h | 10 | 104.9 ± 1.92 | 369 | 317 ± 9 | | | 11.7 ± 0.3 |
| | | | | Cu-HEAp-8 h | 10 | 107.3 ± 2.13 | 325 | 265 ± 8 | | | 15.3 ± 0.2 |
| [37] | Cu | $Al_{0.3}CoCrFeNi$ | Mechanical alloying and sintering | Cu | – | 50 | | | – | – | |
| | | | | HEAp/Cu | – | 75 | – | – | | | – |
| | | | | HEAp/M /Cu | – | 110 | | | | | |
| [115] | Cu | AlCoCrCuFe | Friction stir processing | Pure Cu | – | – | 204 | 117 | – | – | 21.6 |
| | | | | 5 vol% HEAp | 5 | 109 | 123 | 86 | | | 11.4 |
| | | | | 10 vol% HEAp | 10 | 132 | 136 | 91 | | | 7.6 |
| | | | | 15 vol% HEAp | 15 | 150 | 164 | 105 | | | 6.4 |
| [41] | Cu | FeCoNiCrAl | Friction stir processing | As-received Cu | – | 93.82 | 305 | – | – | – | 30.66 |
| | | | | FSPed Cu | – | 78.65 | 275 | – | | | 47.34 |
| | | | | FSPed HEAp/ Cu | – | 209.46 | 281 | – | | | 30 |
| [67] | Mg | $Al_{0.5}CoCrFeNi_2$ | Spark plasma sintering | AZ91 | – | 93 ± 2 | | | 450 | 178 ± 4 | 12.2 ± 0.3 |
| | | | | AZ91-HEAp | – | 138 ± 2 | | | 480 | 209 ± 8 | 13.7 ± 0.5 |
| | | | | AZ91-SiC | – | 123 ± 8 | | | 471 | 204 ± 10 | 12.0 ± 0.4 |
| [83] | Mg | $Al_{20}Mg_{20}Li_{20}Cu_{20}Zn_{20}$ | Powder metallurgy+ microwave sintering + hot extrusion | Mg | – | 47 | 162 ± 15 | 103 ± 9 | – | – | 11.5 ± 0.1 |
| | | | | Mg-2.5HEA | 2.5 | 88 | 199 ± 12 | 154 ± 14 | | | 6 ± 2 |
| | | | | Mg-5HEA | 5 | 95 | 216 ± 9 | 147 ± 7 | | | 8 ± 3 |
| | | | | Mg-7.5HEA | 7.5 | 103 | 220 ± 19 | 147 ± 17 | | | 7 ± 2 |
| [121] | Mg | $Al_{0.5}CoCrCuFeNi$ | Laser cladding | AZ91D | | $HV_{0.1}$98 | – | – | – | – | – |
| | | | | HEAp coating | | $HV_{0.1}$365 | | | | | |
| [64] | Ti | $Al_{0.5}Si_{0.5}FeCoNi$ | Powder metallurgy | MMC 1 | 5 | 453-900 ℃ | – | – | – | – | – |
| | | | | MMC 2 | 10 | 500-900 ℃ | | | | | |
| | | | | MMC 3 | 15 | 535-900 ℃ | | | | | |
| | | | | MMC 4 | 20 | 600-900 ℃ | | | | | |
| | | | | MMC 5 | 25 | 700-900 ℃ | | | | | |
| [65] | Ti | CoCrFeNiMo | Spark plasma sintering | TC4 | – | 359 | 920 | 830 | – | – | 15.8 |
| | | | | TC4-2.5 H | 2.5 | 375 | 1050 | 950 | | | 9.8 |
| | | | | TC4-4.5 H | 4.5 | 380 | 1150 | 1000 | | | 9.0 |
| | | | | TC4-6.0 H | 6.0 | 385 | 1200 | 1050 | | | 5.6 |
| [85] | Ti | $CoCrFeNiMo_{0.2}$ | Hot pressing sintering | 700 ℃ | – | 244.8 | – | – | 1684.6 | 670.1 | 37.5 |
| | | | | 800 ℃ | | 311.8 | | | 1864.1 | 730.1 | 37.2 |
| | | | | 850 ℃ | | 402.6 | | | 2032.6 | 928.2 | 34.4 |
| | | | | 900 ℃ | | 293.2 | | | 1845.1 | 901.3 | 29.7 |
| [134] | W | FeNiCoCrMn | Hot isostatic pressing | HEAp-WHA | – | 456.75 | – | – | 1788 | 972 | 21.0 |
| | | | | Con-WHA | | 322.00 | | | 2250 | 1005 | 46.7 |
| [57] | W | CoCrFeMnNi | Convention sintering + microwave sintering + spark plasma sintering | Convention sintering | – | 439 ± 15 | – | – | 1758 ± 50 | – | – |
| | | | | Microwave sintering | | 431 ± 18 | | | 1962 ± 25 | | |
| | | | | Spark plasma sintering | | 422 ± 12 | | | 2041 ± 45 | | |

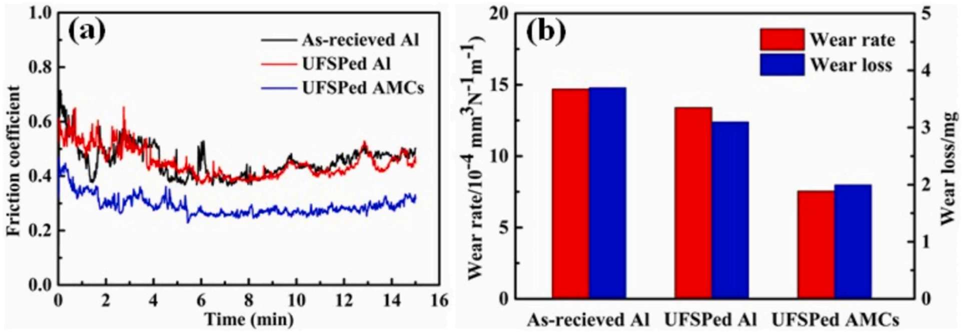


**Fig. 15.** Comparison of (a) the friction coefficient and (b) the wear rate and wear weight loss of as-received Al, underwater friction stir processed (UFSPed) Al and UFSPed Al matrix composites (AMCs).
[104] culled with permission from Elsevier.

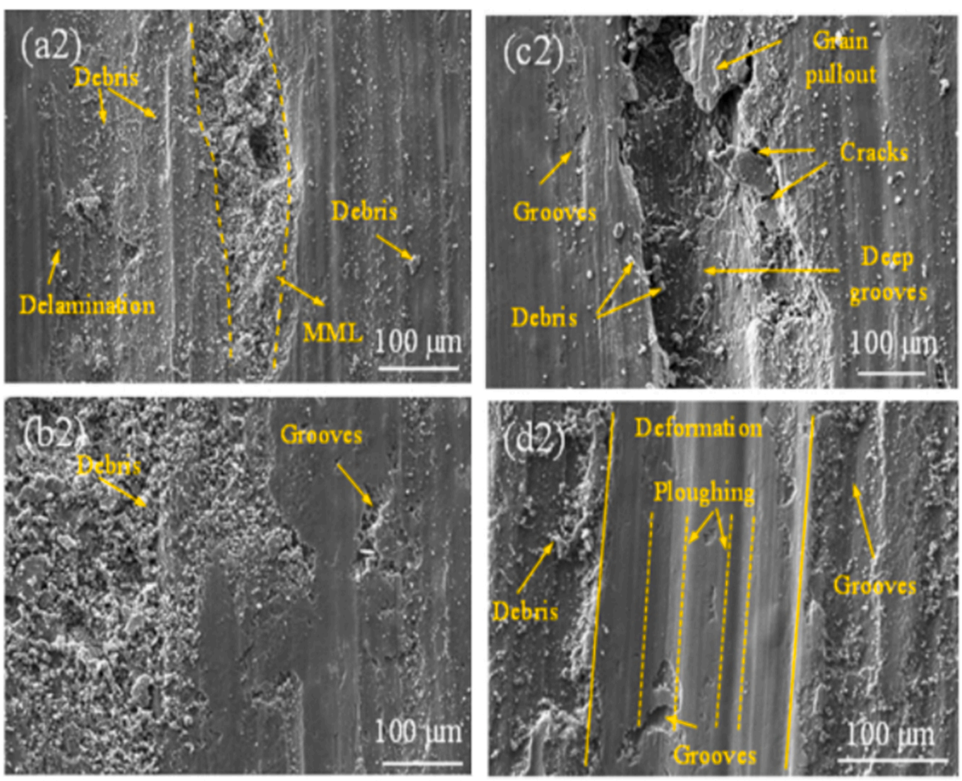


**Fig. 16.** Wear track topography for the different HEAps at a fixed applied load of 30 kN and sliding velocity of 70 mm/s for (a2) AA2219, (b2) 1.5 wt%, (c2) 3.0 wt% and (d2) 5.0 wt% high entropy alloy particle/Al matrix composites (MML – mechanically mixed layer).
[136] culled with permission from Elsevier.

### 3.2.3. *Magnesium matrix*

These HEAs have unique microstructures and characteristics different from traditional alloys, such as Fe- and Ni-based alloys, or intermetallic compounds, such as Ti-Al, Ni-Al and Fe-Al. [138,139] The unique characteristics of these HEAs are derived from the high entropy effect, severe lattice distortion effect, sluggish diffusion effect and cocktail effect. [140] Mg-based alloys find application in various fields, including automotive, communication and aerospace industries, but their optimum utilisation is hindered by their inherent low wear and corrosion resistance. Efforts to resolve this problem have led to the development of laser cladding of Mg alloys with HEAps to enhance their wear and corrosion resistance. [121] Huang *et al.* [121] successfully fabricated an AZ91D Mg alloy surface coated with Al0.5CoCrCuFeNi HEAps via laser cladding, using mixed-elemental powders to boost the wear resistance of the Mg alloy. Selecting $Al_{0.5}CoCrCuFeNi$ HEAps is based on their excellent wear resistance, work-hardening capacity and possession of a single FCC. The dry-sliding wear technique was employed to evaluate the Mg surface's wear resistance. The coating's wear resistance was higher than that of the Mg matrix, and the wear rate was about 2.5 times lower. There were also variations between the Mg matrix surface and the principal wear mechanisms of the coated surface. The matrix's wear mechanism is adhesive wear, whereas the Mg/HEAps' surface undergoes an abrasive wear mechanism. It can be concluded that the wear rate of the Mg/HEAps is lower than the matrix material. However, no substantial data compares this with the wear rate and wear mechanism of conventional Mg-based composites with ceramic reinforcement. Also, more work is required to elucidate the wear rate and wear mechanisms of Mg/HEAp composites. Hence, future research should consider this comparison to obtain composites with optimum wear resistance. This aspect remains an open area of research, with future studies focusing on exploring the effects of different HEAp reinforcement, hybrid AMCs, and different processing techniques and

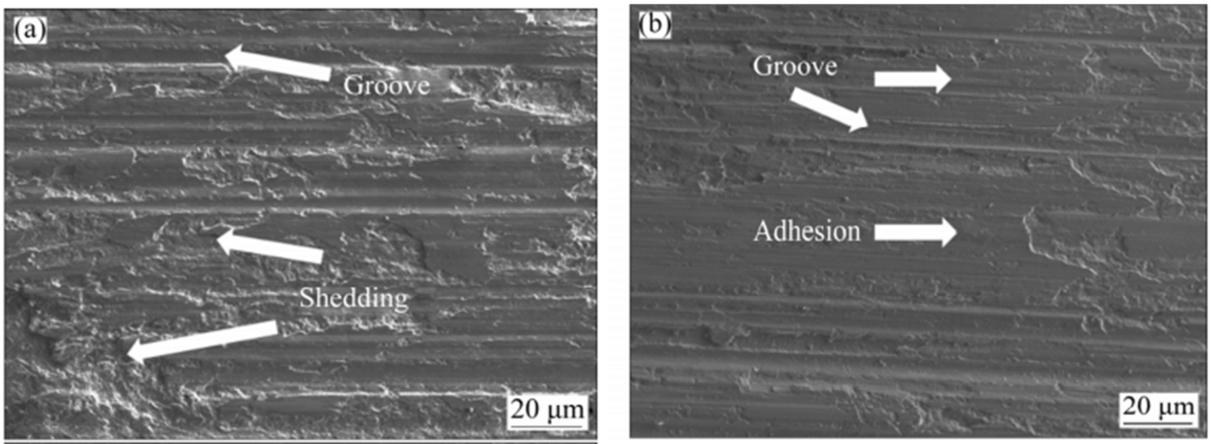


**Fig. 17.** Scanning electron micrographs of the damaged surfaces of (a) high entropy alloy particle/Cu (B) high entropy alloy particle/transition layer/Cu. [37] culled with permission from Elsevier.

heat treatment methods.

### 3.3. Corrosion resistance

Conventional MMCs have been replacing their monolithic counterparts in various technological sectors due to their broad spectrum of properties. However, their corrosion resistance is lower than that of their unreinforced counterparts. This has been attributed to the continuous degradation of the passive film and the formation of voids at the matrix-reinforcement interface, as well as the formation of interfacial phases that aids the galvanic effect. Hence, finding a new type of reinforcement material that can improve both the mechanical and corrosion resistance is of great importance. [141] HEAs are potentially very promising materials for enhancing the corosion resistance of the metal matrix. The cocktail effect in HEA arises from the synergistic interplay among the various elements within HEA. This phenomenon can lead to unforeseen characteristics in HEA, improving aspects like mechanical performance, resistance to corrosion and oxidation, as well as thermoelectric properties. [121,141,142] We discuss the corrosion properties of MMCs reinforced with HEAps in the succeeding sub-sections.

#### 3.3.1. Aluminium matrix

When studies on the corrosion resistance of Al-based composites reinforced with HEAps were evaluated, it was established that mostly introducing HEAps as reinforcement enhanced the corrosion resistance of AMCs compared to their alloy counterparts. However, in conventional ceramic-reinforced AMCs, their corrosion resistance is lower than that of their unreinforced counterparts. The different methods have also been explored to show the individual effect this processing route plays in the unique corrosion potential observed in these composites. Ananisdid *et al.* [141] fabricated a novel AMC reinforced with MoTaNbVW refractory HEAps via powder metallurgy and assessed its corrosion performance in a 3.5% NaCl solution. The obtained Al/HEAp composites and the unreinforced Al alloy were susceptible to localised forms of corrosion in a 3.5% NaCl solution. The HEAps improved the corrosion performance by stabilising the oxide film, and it was observed that there was a decrease in the Al area susceptible to degradation as the weight percent of HEAps increased. However, as the volume fraction of the reinforcement continues to increase, HEAps lead to the formation of discontinuities on the Al oxide film, which can serve as corrosion initiation sites at the Al/reinforcement interface. With the increase in the HEAps, the alloys will be more susceptible to galvanic corrosion, accelerating the dissolution of Al on the Al/HEAp interface. However, uniform dispersion of the reinforcement and lack of intermetallic phases at the interface lower the galvanic effect. Hence, it appears that the corrosion of the matrix plays a major role in regulating the corrosion resistance of the sintered composites. Wang *et al.* [99] evaluated the corrosion resistance of Al-based composites reinforced with CuZrNiAlTiW HEAps. The AMCs had improved corrosion resistance due to the high quality of the sintering and relative density. The Ni and W additions improved the stability of the protective layer formed by passivation, and the HEAp addition improved Al resistance to pitting corrosion.

Thus, HEAps help to reduce the matrix structure's corrosion rate by stabilising the oxide film formed by passivation that serves as a protective layer. However, the authors of the reviewed studies failed to compare the corrosion rate of Al/HEAp composites with the corrosion rate of conventional Al-based composites with ceramic reinforcements. Also, more work is required to elucidate the corrosion rate and its mechanisms for Al/HEAp composites. This aspect remains an open area of research. Hence, future research should consider this comparison to obtain composites with optimum corrosion resistance.

#### 3.3.2. Magnesium matrix

Fig. 18 displays the corrosion characteristics and potentiodynamic polarisation curves of various specimens in a 3.5 wt% NaCl solution. The corrosion resistance of the two samples and the absence of a passivating zone demonstrate that the AZ91D matrix and coating are both susceptible materials. As a result, the $Al_{0.5}CoCrCuFeNi$ HEAp coating fabricated by laser cladding has superior corrosion resistance compared to the AZ91D matrix. When evaluating the corrosion resistance of the active dissolved material using the principle of "the smaller the corrosion current and the higher the corrosion potential, the better the

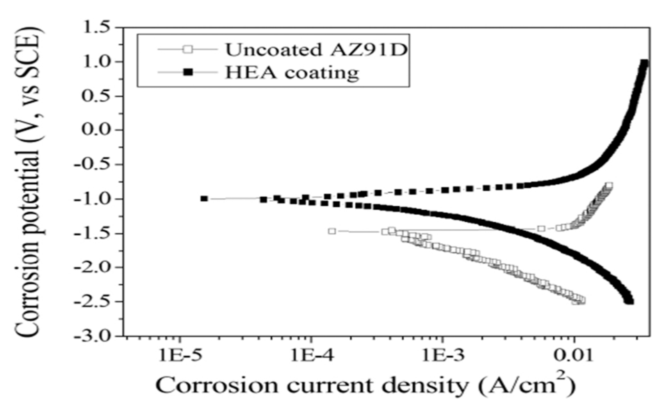


**Fig. 18.** Several specimens' potentiodynamic polarisation curves in 3.5 wt% sodium chloride solution (HEA – high entropy alloy). [121] culled with permission from Elsevier.

corrosion resistance of the material", the fact that the former had a substantially higher corrosion potential as illustrated in Fig. 19. [121].

In conclusion, using HEAps improves the corrosion resistance of matrix material. However, more research needs to be carried out to establish this in other Mg alloys. The authors also failed to compare the corrosion rate of Mg/HEAp composites with the corrosion rate of conventional Mg-based composites with ceramic reinforcements. Hence, future research should consider this comparison to obtain composites with optimum corrosion resistance. Also, the reviewed article is on coating via laser cladding; more work is required to elucidate the Mg/HEAp composites' corrosion rate and its mechanisms. This aspect remains an open area of research; further studies should focus on exploring the effects of different HEAp reinforcement, hybrid AMCs, and different processing techniques and heat treatment methods. The thermal conductivity of MMCs/HEAps is discussed in the succeeding section.

### 3.4. Thermal conductivity

The relentless advancement of the electronic industry imposes ever-increasing service demands on the materials employed in manufacturing heat sinks. It is necessary for the efficiency of high-power electronic components (such as lasers, diodes and thyristors) for the heat produced by their operation to be dissipated. The thermal conductivity of the materials employed in the electronics sector should be similar to that of copper (250 to 400 W/mK). The succeeding section demystifies the thermal conductivity of Cu/HEAp composites. We couldn't find publications on other matrix materials apart from copper.

#### 3.4.1. Copper matrix

Electronic device heat generation has substantially grown as these gadgets have become more complex systems, [142,143] and using conventional packing materials as heat sinks is no longer effective. [41,144] Ceramic-reinforced Cu matrix composites have recently been suggested as potential materials for heat management applications. [144] However, their low ductility, fracture toughness, poor workability and interfacial bonding hinder their employment in this service application. To achieve high thermal conductivity, the Cu matrix and ceramic particles must be properly bonded at the interface and interact well since this interface affects how well the desired high thermal conductivity of ceramic particles as the reinforcing phase can be utilised. [41,144] Therefore, sourcing new reinforcement is especially germane. Zhu *et al.* [41] studied the thermal conductivity of Cu-based composites reinforced with HEAps. The formula $\kappa = \alpha \times \rho \times CP$ was used to calculate the material's thermal conductivity, where α is the specific heat capacity, ρ is the material density and CP is the thermal diffusion. The specific heat capacity of the Cu/HEAps ($0.376\ J.g^{-1}.k^{-1}$) was within the same range as that of the as-received Cu ($0.364\ J.g^{-1}.k^{-1}$). The thermal diffusion of friction stir processed Cu/HEAp composites ($98.56\ mm^2.s^{-1}$) was marginally less than that of as-received Cu ($115.94\ mm^2.s^{-1}$), and the thermal conductivity yielded the same outcomes. The composite's superb thermal characteristics were maintained, and its thermal conductivity ($322.78\ W.(m.K)^{-1}$) reached 87% of the as-received Cu ($371.37\ W.(m.K)^{-1}$). [41].

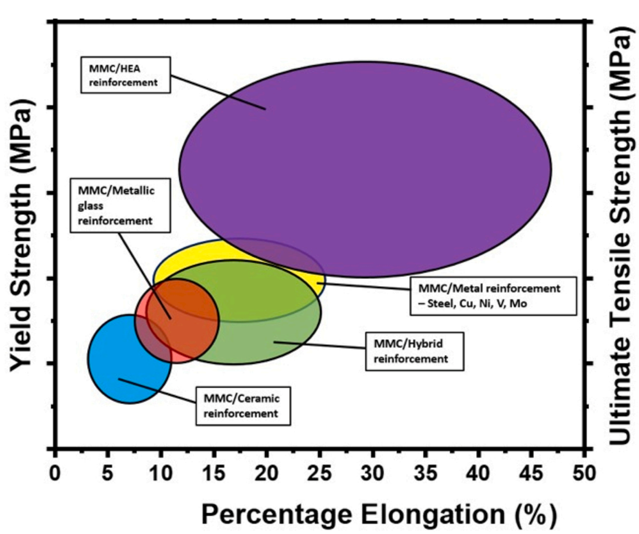


**Fig. 19.** Material selection chart for metal matrix composites (MMCs) with different reinforcement materials (ceramics, metals, metallic glass, hybrid and high entropy alloys (HEAs)).

Zhu *et al.* [41] showed that adding HEAps demonstrated thermal characteristics comparable to that copper matrix, suggesting that Cu/HEAps composites have excellent thermal characteristics and can be employed to manufacture heat sinks in electronic devices. We noticed a dearth of publications in this area, which is an important area for researchers working on MMCs/HEAps to evaluate holistic properties. However, the authors failed to compare the thermal conductivity property of Cu/HEAp composites with that of conventional ceramic-reinforced Cu-based composites. Hence, future research should consider this comparison to obtain composites with optimum thermal conductivity properties. This aspect remains an open area of research; further studies should focus on exploring the effects of different HEAp reinforcement, hybrid AMCs, and different processing techniques and heat treatment methods for improved thermal conductivity properties. We comparatively analyse MMCs reinforced with different reinforcement systems and compared the reinforcement's performance based on their strength-ductility ratio in the next section.

## 4. Comparative analysis on choice of reinforcements in MMCs

We carried out a comparative analysis on MMCs reinforced with different material systems and developed a materials selection chart that compares the reinforcement's performance based on their strength-ductility ratio at ambient temperature. We used the UTS, yield strength and percentage elongation data in supplementary Tables X1, X2, X3 and X4 to develop the materials selection chart in Fig. 19. Conventional metallic systems, hybrid systems, metallic glass and HEA reinforcements outperformed conventional MMCs with ceramics reinforcements. However, the metallic glasses reinforcements performed poorly compared to their metallic counterparts – HEAs and conventional metallic systems – and the hybrid reinforcements. From the chart, HEA reinforcements have great potential and are the most appropriate choice of reinforcement material for designing MMCs with high-performance indices.

## 5. Summary: challenges and suggestions for further research

Malaki *et al.* [145] and Braszczyńska-Malik [146] reported a series of research efforts to design and develop composites with improved mechanical and functional properties. Traditional ceramic reinforcements have been coated with metals to enhance adhesion and interface bonding strength with the matrix. [145] The works reviewed in this paper have demonstrated the progress recorded with the shift from conventional ceramic reinforcements (with metal coatings) in MMCs to alloy-based reinforcements with particular reference to HEAs. Good wetting with high interface bonding strength between the matrix and HEAps reinforcement has been achieved. However, in most reviewed works, little or no comparisons were made with the conventional MMCs. This needs to be done to have a proper overview of the progress made in terms of ductility, fracture toughness and other functional properties using HEAs as reinforcement in MMCs. Also, more work is required to elucidate the mechanisms of matrix-reinforcement interactions with quaternary and more complex alloy systems acting as reinforcement. This aspect remains an open area of research. Developing process technology to control metal matrix-metal/alloy reinforcement reactions and develop composites with improved functional characteristics is another area that is expected to draw research attention in the future. Another challenge involves incorporating additive manufacturing processes to design composite geometries with optimised materials properties. This work is expected to trigger research in these to advance the course of technology.

This review also covered a few studies on the effect of heat treatment methods to improve the process; an area that needs attention. From the studies we reviewed, we observed that the treatment significantly affected the improved mechanical properties. More studies focusing on the wear properties of Al/HEAp composites are needed, and these studies should focus on exploring the effects of different HEAp reinforcements, hybrid MMCs, and different processing techniques and heat treatment methods. Also, our analysis indicated that the particle size of HEAp reinforcements should be refined to enhance its contribution to the hardening effect of HEAps. The effects of particle size, the fraction of HEAp and post-sintering extrusion on strength should be studied. The interfacial bonding characteristics and strengthening and toughening mechanisms between HEAps and the Ti alloy matrix still need further study.

There is a research gap in the corrosion of composite systems. Very few studies to date have considered or provided a holistic view of the corrosion properties of metal matrix-HEAp composite systems. Consequently, this has hindered the practical applicability of these composites. Research in this area is undoubtedly necessary. Studies should be conducted to understand the (1) effects of the production process on the corrosion behaviour of the composites, (2) effects of the HEAp reinforcements, (3) effects of different environments (i.e., acidic, basic and saline), (4) effects of intermetallic compounds formed, and (5) influence of heat treatment on the corrosion resistance of the composites.

Moreover, little attention has been paid to the friction stir process manufacturing of Cu/HEAp composites, particularly considering the reactions at the Cu/HEAp interface; this is an open area of research that could be investigated or exploited. Generally, less research has been done on using HEAps with Cu, Mg, W, Zn and Ti systems; more attention should be given to this research area to unravel the mechanical, wear, thermal, electrical and corrosion properties of these HEAp-reinforced matrices. Finally, using hybrid reinforcements (ceramics and HEAps) has not been well investigated. This is crucial for a better comparison of the influence of the reinforcements on the general properties of the produced composites. The high cost of HEA and their high density remain a major challenge in their utilization as reinforcement in MMCs. Using computational techniques for modelling and simulating experiments should be exploited to reduce experiment costs and prevent resources, time and energy wastage.

## Conclusion

This review discusses the applicability of high entropy alloys as ceramic reinforcement alternatives in metal matrix composites– Al, Cu, Mg, Ti, and W. The influence of reinforcement volume fraction on the mechanical, corrosion, wear, and thermal properties of MMCs reinforced with high entropy alloy particles (HEAps) were discussed. Their fabrication characteristics, heat treatment methods, and interfacial reactions' effect on the mechanical, corrosion, wear, and thermal properties of MMCs are also assessed. This report highlights the performance benefits and certain issues associated with HEAps reinforcement application in MMCs. Also, a comparative analysis on MMCs reinforced with different material systems was carried out and a materials selection chart that compares the reinforcement's performance based on their strength-ductility ratio at ambient temperature was developed. The potential future research directions in this field are suggested. Overall, the application of HEAps as ceramic reinforcement alternatives in MMCs is concluded to have great potential and are the most appropriate choice of reinforcement material for designing MMCs with high-performance indices.

## Ethical statement

The manuscript has been prepared by the contribution of all authors, it is the original authors work, it has not been published before, it has been solely submitted to this journal, and if accepted, it will not be submitted to any other journal in any language.

## CRediT authorship contribution statement

**Aikulola Emmanuel:** Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Anaele Justus:** Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kareem Sodiq Abiodun:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alaneme Kenneth:** Funding acquisition, Supervision, Writing – review & editing. **Bodunrin Michael:** Funding acquisition, Visualization, Writing – review & editing, Supervision. **Adewole Tolulope:** Data curation, Validation, Writing – original draft, Writing – review & editing.

## 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.

## Data Availability

The authors state that the processed data required to reproduce these findings are available in this manuscript.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jalmes.2024.100057.

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