Applicability of metallic reinforcements for mechanical performance enhancement in metal matrix composites: a review

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ABSTRACT

The growing application of metal matrix composites (MMCs) in structural and reliability critical applications has placed higher premium on good combinations of strength, ductility and toughness, in which ceramic reinforced MMCs currently face limitations. Metallic reinforcements have hence come under consideration as replacements of ceramics due to their good wettability and inherent ductility and toughness. This review covers the use of metallic reinforcements in Al, Mg, Cu and Zn-Al metal matrices and the mechanical behaviour of the developed composites. The performance advantages and some concerns with the use of these alternative reinforcements are also highlighted, and the future possibilities in optimizing mechanical performance of MMCs are posited in the paper.

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1. Introduction

New technological delights such as fuel-efficient automobiles, lightweight aircraft and androids have been largely supported by advancement in materials development. Materials scientists are fated to perpetually explore pathways for optimizing material parameters to achieve desirable functional properties to satisfy the stringent service requirements for most technological applications. This materials design process often requires working with material systems which avail the opportunity of tailoring sometimes extreme material characteristics into a whole system to make it service robust and effective in use. Metal matrix composites (MMCs) are material systems that exemplify this description. MMCs are acclaimed for the tailored properties which can be imparted on them by appropriate matrix and reinforcement selections (Anshuman, 2017). Property combinations such as high specific strength and stiffness, low thermal expansion coefficient, good damping capacities, superior wear and corrosion resistance, and good high temperature stability and mechanical properties are common features observed in MMCs (Bauri & Yadav, 2018; Navasisingh et al., 2019).

The attractive property range of MMCs has made them of interest as high-quality materials in several applications. Thus, they are now considered ahead of conventional metallic alloys in several applications spanning sports and recreation, building and civil structures, electrical, electronics and computer systems, security and surveillance, industrial thermal facilities, and transportation (Miracle, 2005; Vasanth Kumar, Keshavamurthy, Perugu, Koppad, & Alipour, 2018). Some metallic alloys which have been utilized as metal matrices for MMCs are aluminium, magnesium, titanium, zinc and copper (Emara, 2017; Hassan & Gupta, 2002a). Conventionally, these metal matrices are reinforced with ceramic materials, among which are aluminium oxide (Al2O3), silicon carbide (SiC), titanium oxide (TiO2), graphite (C) and boron carbide (B4C) (Ramnath et al., 2014; Salih, Ou, Wei, & Sun, 2019). Most of the afore-stated properties of MMCs have been achieved with the use of these ceramic-based reinforcements. However, there are some limitations which have been observed to be associated with the use of ceramic reinforcements in the development of MMCs. These include low ductility and fracture toughness, high abrasiveness, poor wettability/interfacial decohesion, unwanted chemical reactions, recycling difficulties and the high cost of some conventional ceramic reinforcing materials (Alaneme, Ajibuwa, Kolawole, & Fajemisin, 2017; El-Labban, Abdelaziz, & Mahmoud, 2016). Also, high mismatch of the thermal coefficient of expansion between ceramics and metallic materials results in poor thermal fatigue and high dimensional instability.

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in the composites under high cyclic thermal loading (Alaneme, Fajemisin, & Maledi, 2018; Smagorinski et al., 1998). The concerns regarding the limitations of ceramic reinforced MMCs have attained new heights, particularly since MMCs are now deployed as structural and stress-bearing materials in a number of high-tech applications, where structural integrity and safety are crucial service demands. This background is instructive in understanding the motivation for the extensive studies already reported in finding alternative means to enhance properties and functionality of MMCs (El-Labban et al., 2016; Emara, 2017; Hassan & Gupta, 2002a; Thakur, Kong, & Gupta, 2007).

Several approaches and techniques have been recommended to improve properties of MMCs, with their successes and limitations reported (Bodunrin, Alaneme, & Chow, 2015). These include: modifying the processing technique of MMCs (Bains, Sidhu, & Payal, 2016); pre-heat treatment of reinforcing particles (Prasad, Shoba, & Ramanaiah, 2014); coating the particles with wetting agents (Alaneme, Bodunrin, & Awe, 2018); use of hybrid particle reinforcement (Alaneme, Fatile, & Borode, 2014; Lancaster, Lung, & Sujan, 2013); use of nano and sub-micrometre particles; and severe plastic deformation (Goussous, Xu, & Xia, 2010). There are still contentions on the property improvement levels achievable with the use of these methods; consequently, more reliable and pragmatic solutions to this problem are still being sought. It is noteworthy to mention that research in this area has also witnessed the consideration of agro and industrial derivatives (rice husk ash, bamboo leaf ash, ground-nut shell ash, red mud, fly ash, quarry dust, steel chips) as sole or partial (when mixed with conventional ceramics) replacements for conventional reinforcement materials used in MMC development (Arora & Sharma, 2017; Bahrami, Soltani, Pech-Canul, & Gutiérrez, 2015; Fathy, El-kady, & Mohammed, 2015). These studies have established the promise of these reinforcements for metal matrices, particularly from cost-saving perspectives, but the developed composites still have not addressed the functional limitation of conventional ceramic reinforcements.

Recently, attention have been channelled towards the use of metallic materials such as pearlitic steels, stainless steel, iron, copper, nickel, titanium and metallic glasses as principal reinforcement in MMCs (Iglesias, Jiménez, Bermúdez, Rao, & Chandrasekar, 2013; Sankaranarayanan, Jayalakshmi, & Gupta, 2012; Ye & Liu, 2005). Hard metallic phases are considered as reinforcements because of their inherent ductility and toughness. Also, they have good wettability with metal matrices resulting in good interfacial bonding between reinforcement and matrices which gives rise to superior mechanical properties such as hardness, strength and ductility as well as other engineering properties (Yadav & Bauri, 2010).

There is no doubt that the development of MMCs with improved properties for structural applications will continue to be a fascinating area of research. Reviews have been written to cover different aspects of the evolution in MMC development. These include reviews which presented discussions on peculiarities of metal matrices such as Al and Mg (Lyod, 1994; Ramnath et al., 2014; Torralba, da Costa, & Velasco, 2003). Treatises on MMCs have also included findings on the influence of different reinforcement types on metal matrices ranging from broad classification of fibre and particulate reinforcements to specifics using ceramics and carbon nanotubes (Chawla & Shen, 2001; Chou, Kelly, & Okura, 1985; Ibrahim, Mohamed, & Laverna, 1991; Nair, Tien, & Bates, 1985; Thostenson, Ren, & Chou, 2001). Other reviews on MMCs limited to treatment of specific classes of MMCs are also available in the literature (Bains, Sidhu, & Payal, 2016; Bodunrin et al., 2015; Casati & Vedani, 2014; Srivastava, Dixit, & Tiwari, 2015; Yadav & Bauri, 2010). The existing reviews on the subject have primarily addressed issues centred on the development and performance of MMCs reinforced with ceramic materials. Since the emergence of research on the viability of metallic materials as substitutes to ceramics in the reinforcement of MMCs over two decades ago, there have been very few reviews highlighting their importance and potential downsides. This review attempts to fill this gap in the literature. The review chronicles some of the leading research which has shown the promise of metallic reinforced metal matrices in service applications. It also analyses some of the challenges likely to be contended with the use of these reinforcements in the long run and posits the future path of research on the development of MMCs with improved mechanical performance, particularly enhanced combination of strength, ductility and toughness.

2. Metallic-based reinforcements for metal matrices

The previous section highlighted some of the concerns with the use of ceramics as reinforcements in MMCs. This section is dedicated to studies carried out on the use of metallic-based reinforcements in different metallic matrices. The aim is to ascertain whether there are any significant improvements in properties such as toughness, ductility and good wettability, which are some of the limitations tied to the use of ceramic-based reinforcements.
2.1. Aluminium base metal matrix composites

Aluminium matrix composites (AMCs) are currently utilized in a lot of technological applications. They offer an excellent balance of cost, functionality and processability. AMCs are acclaimed for the broad spectrum of properties which they can be tailored to possess with appropriate selection of reinforcements and processing schemes. Rarely is it found in any other class of material where property combinations of good specific strength and stiffness, low coefficient of thermal expansion (CTE), good tribological properties, good oxidation and corrosion resistance, and a relatively low processing cost are obtained as observed in AMCs (Kerti & Toptan, 2008; Surappa, 2003; Suresha & Sridhara, 2010). That is why they are very versatile and have been applied in virtually every important technological sector, such as aerospace materials, automobile, defence, heat exchange components, sports and recreation (Pandi & Muthusamy, 2012; Prasad & Asthana, 2004; Salih, Ou, Sun, & McCartney, 2015). The growing application of AMCs that are primarily reinforced with ceramics as structural materials has justified the need for improved ductility and toughness. Metallic-based reinforcements have been used in AMCs with the hope of addressing these challenges. The observations from their use are presented in the following paragraphs.

2.1.1. Metallic reinforcements

Fathy et al. (2015) studied the microstructure, mechanical and magnetic properties of powder metallurgy processed Al matrix composites reinforced with 5, 10 and 15% iron powder. It was observed that the Fe powders were evenly dispersed in the matrix, and a significant increase in hardness, compressive strength and ductility was achieved. Also, the mechanical properties improved with an increase in the mass fraction of the Fe powders. For instance, Al-15Fe had 550 MPa compressive strength and a plastic strain of 65%. This was attributed to dispersion strengthening of the Al matrix by the Fe powders and the formation of intermetallic compounds as mass fraction of the Fe powders increased. Al-15Fe composite had the best combination of mechanical properties of the composites produced. The property improvement reported in the study was, however, accompanied by an overall increase in densities of the Fe reinforced Al matrix composites, attributed to the higher density of Fe (7.8 g/cm³) compared with pure Al (2.8 g/cm³).

Pal et al. (2015) embarked on a study to establish the optimum composition that would yield the best combination of mechanical properties in stir cast Ni reinforced Al matrix composites containing varied weight per cent (10, 20, 30 and 40) of Ni. It was observed from the study that there was no consistency in the variation of the mechanical properties with Ni concentration. This was attributed to Al–Ni interaction in each composite composition coupled with factors such as impurities, particle size and defects, among others. However, the Al matrix composite composition reinforced with 20% Ni was observed to showcase the best combination of hardness, tensile strength and thermal conductivity. The property combination exhibited by this composition was considered to be suitable for the production of cylinder walls, engine cooling pads, cycle frames and pistons. However, the toughness and ductility of the composite were not reported and the high cost of Ni may be a limiting factor for such high volume per cent composite production.

Yadav and Bauri (2010) investigated the mechanical properties of Ni (7%) particulate reinforced Al-based composites processed using friction stir processing (FSP). FSP was used to avoid the formation of intermetallic Al3Ni often produced using other conventional processing routes such as disintegrated melt deposition. The results showed that FSP led to the attainment of homogeneous dispersion of the Ni particles in the Al matrix and the achievement of good matrix/particle interfacial bonding. It was also observed that the Al matrix was extensively grain refined, which was due to dynamic recrystallization that occurred during FSP. The Ni reinforced Al matrix composite had thrice the value of the yield stress reported for the unreinforced Al. Generally, the Ni reinforced Al had higher strengths compared with the unreinforced Al. This was attributed to the good Al matrix/Ni particle interfacial bonding, which facilitates effective load transfer from the matrix to the stronger Ni particles via the matrix/particle interfaces. The strengthening mechanism was also associated with the hindrance of dislocation movement by the Ni particles and boundary strengthening arising from the Al matrix grain refinement. The most remarkable feature of the composites is that their significant strength increase (from 90 to 127 MPa for ultimate tensile strength (UTS)) did not result in a substantial compromise in ductility (from 35 to 25%). The good ductility levels retained by the Ni reinforced Al composites was attributed to the inherently ductile Ni particles and the non-existence of embrittlement intermetallic phases in the composite.

Kumar and Devi (2014) studied the mechanical behaviour of Al6061 alloy reinforced with Cu particulates of varying mass concentrations. The Al-Cu particulate composites were successfully processed using a die casting method. The microstructural analysis revealed that the copper particulates were uniformly dispersed in the Al6061 matrix. The
microstructures were also observed to consist of coarse grains of Al with Cu intermetallic particles at the grain boundaries. The hardness values of the Cu reinforced AMC composites increased as the weight per cent of Cu particulate increased up to 8 wt.%. and then decreased for the composite with 10 wt. % of Cu particles. The same trend as that of hardness was also observed for the tensile strength and impact strength of the Cu reinforced AMC composites.

Gopi Krishna et al. (2018) assessed the mechanical behaviour of stir cast 5–15 wt.% Cu powder reinforced A356 matrix composites. In the study, the potentially strong and continuous particle/matrix interface which can be harnessed with the use of metallic particles as reinforcement in metallic matrices was explored. The reinforcement in this case was Cu powder of 53 μm average particle size, and the stir casting process adopted followed standard processing procedures. The composites were observed to possess higher hardness, UTS, yield strength, modulus of elasticity and ductility than the A356 unreinforced alloy. The strengthening mechanism was reported to be due to the combination of solid solution strengthening from the partially dissolved Cu powder in the alloy matrix and dispersion strengthening from the undissolved Cu particles. Also, refinement in composite matrix grain size with increase in the volume fraction of the Cu powder was linked to the improved mechanical performance observed in the Cu powder reinforced A356 composites produced.

Emara (2017) compared the mechanical properties of powder metallurgy processed unreinforced aluminium, aluminium matrix composites reinforced with 5, 7.5 and 10 wt.% steel machining chips (SMC), and those reinforced with 5 and 10 wt.% SiC. It was observed that the per cent porosity in the steel chip reinforced composites was lower than that for the SiC reinforced composites. The Vickers hardness, yield strength and UTS of the steel chip reinforced composites were reported to be higher than that of the pure Al and SiC reinforced composites. Also, the strength properties of the composites improved with increase in weight per cent of SMC. The largely superior strength properties of the steel chip reinforced AMCs was ascribed to the good Al matrix/SMC interface bonding. This facilitated stress transfer and distribution from the Al matrix to the stronger SMC. Also, the 5% steel chip reinforced composites had high percentage elongations (25%), comparable to that of the unreinforced Al (28%) and SiC reinforced composites (13%). The high ductility of the 5% steel reinforced composite was linked to the strong and continuous Al matrix/steel chips interface and the inherent ductile nature of the steel chips.

Alaneme et al. (2018) reported on the mechanical behaviour of stir cast Al-Mg-Si alloy matrix composites reinforced with steel, SiC and a mixture of steel and graphite particles. The results show that within the range of 4–8 wt.% steel particle reinforcement utilized, the hardness of the composites increased to a maximum of 11%. The UTS, specific strength and fracture toughness of the composites equally increased with increase in the weight per cent of steel particles. The ductility was the only exception where marginal reduction was observed with increase in the concentration of steel particles. Noteworthy is the fact that the steel reinforced compositions had superior strength, toughness and ductility characteristics compared with the composite composition reinforced with 8 wt.% SiC. The improved properties were reasoned to be connected with the enhanced grain refinement, strong matrix/steel particles interface and higher inherent ductility of the steel particles over that of SiC.

Selvakumar et al. (2017) assessed the effectiveness of Mo as potential reinforcement for Al matrices. The study was conducted on Al matrix composites produced with varied volume fractions of Mo (6, 12 and 18%) using FSP. The Mo particles were retained in elemental form in the composites, inferring that there were no interfacial reactions; also, the absence of pores at the interface indicates good bonding between the Al matrix and Mo particles (reinforcement). The Mo particles were also homogeneously distributed in the matrix independent of distance from the stir zone. Grain refinement was observed in the microstructure, which is due to dynamic recrystallization and the pinning effect of the Mo particles on the boundaries, which hindered grain growth. The tensile tests revealed that the UTS of the composites was higher than the unreinforced Al matrix and this was linked to the good interfacial bonding and high dislocation density in the composites. The tensile testing also showed that there was no substantial loss of ductility in the Mo reinforced Al matrix composite. The relatively ductile nature of the composite was attributed to the inherent deformability of the reinforcement and low work hardening of the Al matrix around the Mo particles. The enhanced ductility of the composites is further reflected in the fracture mode of the composites, which is observed from Figure 1 to be characterized by dimple rupture.

Huang et al. (2018) employed multi-pass submerged friction stir processing (SFSP) to reinforce 5083Al matrix with Ti particles. The multi-pass SFSP was complemented by water cooling, which promoted uniform distribution of the reinforcements in the matrix. Also, the water cooling contributed to mutual diffusion of elements preventing formation
of interfacial reaction products at the reinforcement matrix interface. Ultrafine grains with average size of \( \frac{1}{24} \) \( \mu m \) were observed in the microstructures of the produced composites, and this was attributed to dynamic recrystallization (continuous) which took place during the processing and the inhibition of grain growth by the fast cooling rate offered by water cooling. The tensile testing results showed that the SFSP processed Al matrix composite exhibited a 46 and 55% increase in yield strength and UTS, respectively, compared with the unreinforced Al alloy. The improved strength was attributed primarily to the extensive grain refinement in the composites. The strengthening mechanisms of the composites were concluded to be the contributions of grain boundary strengthening, quench strengthening and load transfer. The composites retained a considerable amount of ductility, and this was evident in the appearance of the fractured surfaces which consisted of dimples. Figure 2 shows the result of the Ti reinforced Al composite which showcased the higher strengths and slightly reduced ductility of the composites.

Abraham, Dinaharan, Selvam, and Akinlabi (2019) studied the mechanical response of vanadium particle reinforced Al matrix composite prepared using FSP. Analysis of the microstructures of the composites using microscopic techniques revealed homogeneous dispersion of vanadium particles and the absence of intermetallic particles in the aluminium matrix. The grain structure in the developed composites was observed to be fine and equiaxed due to dynamic recrystallization. The presence of the vanadium particles increased the UTS from 215 MPa in the Al alloy to 268 MPa in the composite. The strengthening in the composite was attributed to grain refinement, effective load transfer, presence of strong interfaces and even particle dispersion. The elongation in the vanadium reinforced composite was 20%, which was just a slight drop compared with what was observed in the unreinforced alloy, indicating that the presence of this reinforcement improved the plastic flow of the matrix. The ductility of the composites was attributed to the inherent ductility and thermal conductivity of vanadium. Further confirmation of the improved ductility is evident from the fracture surface appearance (Figure 3), which revealed the presence of dimples, which is a fingerprint feature of ductile fracture.

2.1.2. Metallic glass reinforcement

Metallic glasses are non-crystalline metallic materials with a disordered atomic scale structure formed
when liquid alloy solidifies at critical cooling rates faster than that required for long-range order to be established by the atoms of the metallic materials (Ashby & Greer, 2006). Metallic glasses have an unusual combination of mechanical properties, such as high hardness, high strength, high elastic strain limits, low ductility and fracture toughness, attributed to their non-crystalline structure and absence of microstructural defects (Ashby & Greer, 2006; Saida, Matsushita, Li, & Inoue, 2000). Metallic glasses have since been considered as novel reinforcement for metal matrices in a bid to harness the promising properties they possess (Lee et al., 2004). The use of metallic glasses as reinforcement is also predicated on the belief that metallic glasses, being inherently metals, would have better compatibility with metal matrices resulting in better interface bonding and enhanced properties of MMCs. The following are some of the outcomes from the use of metallic glasses as reinforcement in AMCs.

Scudino et al. (2009) carried out a study on Al-based composites containing a varying volume per
cent of Zr$_{57}$Ti$_{8}$Nb$_{2.5}$Cu$_{13.9}$Ni$_{11.1}$Al$_{7.5}$ glassy powders. Powder metallurgy processing was adopted for the composites’ production using pure Al and Zr$_{57}$Ti$_{8}$Nb$_{2.5}$Cu$_{13.9}$Ni$_{11.1}$Al$_{7.5}$ metallic glass. It was observed that adding 60 vol.% of metallic glass in the Al matrix raised the compressive strength from 155 to 250 MPa; also, substantial strain to fracture ranging between 40 and 70% was observed in the composite containing 40 vol.% of the metallic glass. The increase in compressive strength was observed to be sensitive to the volume per cent of the metallic glass. The study showed that the composites with 60 vol.% of the metallic glass had higher strength, while the ones with 40 vol.% of the metallic glass reinforcement phase had better ductility. It was noted from the study that dislocation strengthening solely could not suffice in explaining the mechanism responsible for the strength increase in the metallic glass reinforced composites. It was, however, established that the large size and high volume per cent of the metallic glass powders resulted in more effective load transfer by shear, which led to the increased strength observed. The higher volume fraction of the metallic glass phase was also reported to contribute to local particle contiguity, which increases particle interaction – making the connected particles behave like short fibres. This effect was stated to improve the compressive strength of the composites. A reverse trend was observed for the composites with respect to ductility, where higher values are observed at lower volume fractions of the reinforcement and lower values at high volume fractions. This implies that the local particle contiguity also affected the composites’ ductility, arising from increased particle interaction in the reinforcing phase of the AMC.

Aljerf et al. (2012) studied the mechanical behaviour of sintered Al6061 alloy-based composites reinforced with [(Fe$_{1/2}$Co$_{1/2}$)$_{75}$B$_{20}$Si$_{5}$]$_{96}$Nb$_{4}$ metallic glass. The metallic glass particles exhibited viscous behaviour within the selected sintering temperature range, which resulted in low or zero composite porosity. Results from compressive tests showed that the [(Fe$_{1/2}$Co$_{1/2}$)$_{75}$B$_{20}$Si$_{5}$]$_{96}$Nb$_{4}$ metallic glass raised the yield strength of Al6061 alloy from 270 to 570 MPa. Also, the strain to fracture of the composite was approximately 13%, which is a remarkable level of plastic deformability for a yield strength increase of up to 110% (270–570 MPa). The significantly improved strength of the composite is plausibly on account of the higher hardness of the metallic glass compared with the Al alloy. When stress is applied to the composite, the Al alloy matrix transfers much of the load to the elastically stronger metallic glass.

Wang et al. (2014) carried out an investigation to ascertain the suitability of a Mg-based metallic glass for the reinforcement of Al. In the study, uniaxial hot pressing was adopted for the synthesis of Mg$_{65}$Cu$_{20}$Zn$_{5}$Y$_{10}$ metallic glass particle reinforced Al-based composite while the mechanical properties were assessed using compression testing. The investigation revealed that even dispersion of the metallic glass particles in the Al matrix and good reinforcement–matrix bonding led to significant strength enhancement complemented with good plastic deformability (in comparison with pure Al). For instance, yield strength enhancements of ~ 222 and 251% (relative to the Al matrix – 63 MPa) were achieved for 10 and 30 vol.% Mg$_{65}$Cu$_{20}$Zn$_{5}$Y$_{10}$ metallic glass particle addition; while compressive strength increases of ~ 87 and 145% were achieved for the same range of compositions. Satisfactory plastic strain to fracture of 25% was reported for the Al-10 vol.% Mg$_{65}$Cu$_{20}$Zn$_{5}$Y$_{10}$ composite composition. A validated matrix-strengthening mechanism incorporating a modified shear lag model predicted that matrix dislocation strengthening due to the metallic glass particles would be a key determinant of the improved mechanical properties exhibited by the composites.

Zheng et al. (2014) studied the microstructure and mechanical properties of powder metallurgy processed Fe-based metallic glass (FMG) particle reinforced Al-2024 matrix composites. The processing resulted in the production of nanostructured Al-2024 matrix (~ 30 nm) containing well-dispersed FMG particles. It was observed that the compressive strength value of the AMCs was higher than the Al-2024 alloy. The FMG reinforced Al-2024 matrix composites had yield and fracture strengths of 403 and 660 MPa, respectively, and also had 12% plastic strain at fracture. The strengthening mechanism in the FMG reinforced Al-2024-based composite was linked to matrix grain refinement and uniform dispersion of the FMG particles.

2.1.3. Summary

The literature surveyed shows largely that metallic-based reinforcements in Al MMCs show a superior blend of strength and ductility compared with ceramic reinforcements. The reviews show that metallic materials (including selected metallic glasses) as reinforcement are more reliable than ceramics in preserving the ductility of Al and Al alloy matrices. Also noteworthy is the sensitivity of ductility to concentrations of the reinforcing phase, where it was observed that a decline in ductility corresponded with increased weight per cent of the metallic reinforcements in the composites. Some of the studies, however, did not state the exact ductility levels attained and how they compare with that of the unreinforced Al-based alloys which served as the
metal matrix. A few of the works reported an increase in the composite density compared with ceramic reinforcements, which is largely due to the high density of transition metals (elements) that are predominantly used as reinforcement (Fe, Ni, Cu). It was also noted from some of the studies that the processing technique adopted for the composite production can influence the matrix/reinforcement interface integrity, which contributed to the strengthening and ductility values achieved in the composites. Table 1 summarizes at a glance the influence of metallic-based reinforcements on Al matrices in terms of mechanical response and the mechanisms responsible for such behaviours.

2.2. Magnesium base metal matrix composites

The quest for lighter structural materials for several technological applications has drawn attention to magnesium alloys in recent times (Rashad, Pan, Asif, She, & Ullah, 2015). Magnesium alloys are known to have good castability, good machinability, high damping capacity, high dimensional stability, good recyclability and good biocompatibility (Alaneme & Okotete, 2017). In addition to the well-known poor formability limitation of Mg alloys, they also have low absolute strength, especially at elevated temperatures, and are therefore limited to applications up to 120°C (Ye & Liu, 2004). Magnesium composites were developed to increase the absolute strength of Mg-based materials at high temperatures. Xiuqing et al. (2005) reported that the success achieved with the use of SiC particles to improve the specific strength and stiffness at room and elevated temperatures and creep resistance of Mg-based alloys was limited by agglomeration of reinforcement particles and an unclean reinforcement/matrix interface. Research is therefore ongoing to ascertain the suitability of other reinforcements for improved elevated temperature strength and ductility of Mg-based composites.

2.2.1. Metallic reinforcements

2.2.1.1. Nickel. Hassan and Gupta (2002b) conducted a study on disintegrated melt deposition and hot extrusion processed Mg composite reinforced with elemental nickel particles. The analysis of the microstructure of the produced Mg-based composite showed that there was uniform dispersion of nickel particulates in the Mg matrix, minimal porosity in the composites, and good integrity between matrix/nickel particulates and matrix/Mg-Ni intermetallic interfaces. Investigation of the properties of the Mg-based composite showed that dimensional stability was achieved in pure Mg when nickel particulates were added. Furthermore, the results from mechanical testing revealed improvements in hardness values, 0.2% yield strength, UTS and stiffness of the composites. The observed improvements were established to be sensitive to weight fractions of nickel in both elemental and intermetallic form. However, the Mg matrix ductility declined with an increasing amount of nickel. The improvement in hardness of the composites was attributed to the harder nickel particles and Mg2Ni intermetallics and the increased resistance to localized deformation elicited by these particles. Also, the improved tensile properties were linked to uniform distribution of nickel and the strengthening effect of the Mg2Ni intermetallics, coupled with effective matrix to reinforcement load transfer. The study also stated that the observed improvement in mechanical properties with the use of nickel was much higher than the improvement recorded in AZ91 Mg alloy reinforced with SiC of higher volume per cent of the reinforcement.

2.2.1.2. Copper reinforcements. Hassan and Gupta (2003) also carried out a comparative study on copper and copper particle reinforced Mg composites processed by disintegrated melt deposition and hot extrusion. The microstructural analysis revealed evenly dispersed Cu and Mg–Cu-based intermetallic particulates in the Mg matrix, and good Mg matrix/particulate interface integrity. The porosity levels observed in the composites were low (0.009% for Mg–18Cu), an indication of the reliability of the processing methods utilized in the study. The results revealed that the increased amount of elemental Cu and the intermetallic (Mg2Cu), led to improved hardness, stiffness and UTS. Improvement in 0.2% yield strength of Mg was consistent for Cu additions up to 18.0 wt.%. The Mg matrix ductility was found to decrease with increase of Cu particulates from 10 to 26 wt.%. The improvement in mechanical properties was ascribed to even dispersion of the reinforcements in the Mg matrix, high modulus of the reinforcing phase, good Mg matrix/Cu particulate interfacial integrity and the formation of the Mg2Cu intermetallic phase. The reduced ductility was attributed to high amounts of brittle Mg2Cu intermetallics at the particle–matrix interface and at the core of the matrix.

Ho et al. (2004) studied the mechanical behaviour of disintegrated melt deposition and hot extrusion processed AZ91 Mg alloy reinforced with fine copper particulates. A near even dispersion of the copper particulates and other second phases was observed in the microstructure of the composite. Other observations in the composites’ microstructure include good integrity in the Cu–Mg interface, good intermetallics-Mg alloy interface integrity and
Table 1. Summary of the mechanical response of Al matrix composites developed with metallic-based reinforcements.

| Matrix + reinforcement                | Processing technique             | Yield strength (MPa) | UTS (MPa) | Elongation (%) | Yield strength (MPa) | UCS (MPa) | Elongation (%) | Strengthening/toughening mechanisms                                                                 |
|--------------------------------------|----------------------------------|----------------------|-----------|----------------|----------------------|-----------|----------------|----------------------------------------------------------------------------------------------------------------------|
| Al + Fe (Fathy et al., 2015)         | Powder metallurgy                | 550                  | 65        |                |                      |           |                | Dispersion                                                                                                            |
| Al + Ni 10%                          | Stir casting                     | 1295                 |           |                |                      |           |                | Interaction between matrix and reinforcement                                                                     |
| 40% (Pal et al., 2015)               |                                  | 918                  |           |                |                      |           |                |                                                                                                                      |
| Al + Ni (Yadav & Bauri, 2010)        | Friction stir processing         | 123                  | 25        |                |                      |           |                | Grain boundary/ductile nature of reinforcement                                                                     |
| Al + Cu 4%                           | Die casting                      | 121.45               | 10.26     |                |                      |           |                | Solid solution, presence of intermetallics                                                                        |
| 6%                                   |                                  | 129                  | 14.56     |                |                      |           |                |                                                                                                                      |
| 8%                                   |                                  | 131.37               | 6.02      |                |                      | 86.57     | 4.86           |                                                                                                                      |
| 10% (Kumar & Devi, 2014)             |                                  |                      |           |                |                      |           |                |                                                                                                                      |
| Al + steel chips 5%                  | Powder metallurgy                | 176                  | 25        |                |                      |           |                | Interfacial bonding/plastic strain capacity of reinforcement                                                         |
| 7.5%                                 |                                  | 220                  | 20        |                |                      |           |                |                                                                                                                      |
| 10% (Emara, 2017)                    |                                  | 260                  | 17        |                |                      |           |                |                                                                                                                      |
| Al + steel chips 4%                  | Double stir casting              | 125 ± 5              | 14 ± 5    |                |                      |           |                | Grain refinement, interface bonding/intrinsic toughening of reinforcement                                           |
| 6%                                   |                                  | 138 ± 5              | 13.6 ± 5  |                |                      |           |                |                                                                                                                      |
| 8% (Alaneme et al., 2018)            | Friction stir processing         | 150 ± 5              | 13 ± 5    |                |                      |           |                | Good interface bonding, grain refinement/plastic flow and thermal conductivity of reinforcement                     |
| Al + Mo 6%                           |                                  | 278 ± 2              | 9 ± 2     |                |                      |           |                |                                                                                                                      |
| 12%                                  | Multi-pass submerged friction stir processing | 303               | 7 ± 2     |                |                      |           |                | Grain refinement, grain boundary/absence of intermetallics, plastic deformability of reinforcement                   |
| 18% (Selvakumar et al., 2017)        |                                  | 246                  | 432       | 23.2           |                      |           |                |                                                                                                                      |
| Al + V 12%                           | (Abraham et al., 2019)           | 268                  | 20        |                |                      |           |                | Grain refinement, effective load transfer, presence of strong interfaces, consistent dispersion/ductility and thermal conductivity of reinforcement |
| Al + Zr12Ti13Nb25Cu13Ni11Al7.5Fe40%  | Powder metallurgy                | 200                  | 30        |                |                      | 250       | 10             | Load transfer by shear                                                                                              |
| 60% (Scudino et al., 2009)           |                                  | 250                  | 10        |                |                      |           |                |                                                                                                                      |
| Al + [(Fe1/2Co1/2)75B20Si5]96Nb4      | Powder metallurgy                | 570                  | 600       | 12             |                      |           |                | Higher mechanical strength of reinforcement                                                                       |
| (Aljerf et al., 2012)                |                                  |                      |           |                |                      |           |                |                                                                                                                      |
| Al + Mg65Cu20Zn5Y10 10%              | Uniaxial hot pressing            | 203                  | 247       | ~25            |                      | 221       | 323            | Indirect strengthening by                                                                                           |
| 30% (Wang et al., 2014)              |                                  |                      |           |                |                      | 403       | 660            | increased dislocation density                                                                                       |
| Al + Fe-based metallic glass         | Powder metallurgy                | 403                  | 660       | 12             |                      |           |                | Grain refinement, uniform distribution of reinforcement                                                             |

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minimal porosity. The results from mechanical testing showed that the copper particles increased the elastic modulus, 0.2% offset yield strength and UTS of the AZ91Mg matrix composite. However, the composite ductility was marginally lower compared with the value for AZ91Mg matrix. The increase in strength in the composite was attributed to the homogeneous dispersion of elemental copper particles in the AZ91Mg matrix, strong secondary phases in the AZ91Mg matrix and the effective load transfer between the AZ91Mg matrix and the reinforcement/second phases. The ductility reduction of the composite was ascribed to the intrinsically brittle intermetallic phases in the matrix which serve as sites for crack nucleation.

Wong and Gupta (2007) developed Mg/Cu nanocomposites using microwave assisted rapid sintering and hot extrusion processing. The microstructure of the synthesized Mg-based composite showed low porosity and the existence of an unbroken network of nano-size Cu and intermetallic (Mg₂Cu) phases contiguous to the grain boundaries. The presence of the nano-size Cu particulates marginally improved the CTE value of the magnesium matrix. Improvement in mechanical properties (hardness, elastic modulus, 0.2% yield strength, UTS and work to fracture of the matrix) was also observed in the Mg/Cu nanocomposites. The increased hardness of the Mg/Cu nanocomposites was linked to the harder Cu nanopowders and intermetallics formed in the composite and the constraint posed by the particles to localized deformation. The increase in tensile properties was attributed to work hardening due to Mg matrix/Cu nanopowder strain misfit, thermal expansion coefficient mismatch-enabled internal stresses, Orowan strengthening, grain size reduction and effective Mg matrix to nano-Cu/Mg₂Cu load transfer. The study also established that a 0.6% volume percentage of Cu nanopowder was the optimum required for improved tensile properties, as higher volume percentage (1.0%) of Cu nanopowder led to a decline in the tensile properties of the composites. A slight decrease in ductility (from 6.1 to 5.9%) was also observed between pure Mg and 0.3 wt.% Cu reinforced Mg. The decrease was, however, more pronounced with increased reinforcement additions (0.6Cu and 1.0Cu).

2.2.1.3. Titanium-based reinforcements. Hassan and Gupta (2002a) carried out a different study on titanium particulate reinforced magnesium composites developed by disintegrated melt deposition and hot extrusion processing. The efficiency of the processing technique for Mg-based composite reinforced with titanium particulates was evident in the uniform distribution of titanium particulates in the Mg matrix and strong Mg matrix/Ti particulate interface integrity. Microstructural analysis also showed minimal presence of porosity in the produced composites. Only marginal change in dimensional stability was observed in the Mg-Ti composite compared with unreinforced Mg; the reason for this marginal increase was not, however, discussed in the study. Significant increases in 0.2% yield strength and ductility were also hallmarks of the composite, but the UTS decreased slightly. The increase in yield strength was attributed to Mg and Ti thermal expansion coefficient mismatch-enabled matrix dislocation strengthening and the strong Mg matrix/Ti particle interface. The decrease in UTS was attributed to the onset of localized damage as the applied stress increased beyond the yield point. The improved ductility of the Mg composite reinforced with titanium is noteworthy since there are few records of improved ductility with the use of metallic reinforcements over the unreinforced Mg. The increase in ductility of the composite over the unreinforced magnesium was attributed to Ti diffusional dissolution facilitated Mg matrix softening.

Xi et al. (2005) developed MB15 magnesium matrix composite reinforced with Ti-6Al-4V particle (TCP) using the powder metallurgy route. A silicon carbide reinforced MB15 Mg composite was also produced and used as a basis of comparison for the results obtained for the TCP reinforced Mg-based composite. An even dispersion of TCP, good MB 15 Mg matrix/TCP interface bonding and a finer grain size compared with the unreinforced MB15 were achieved in the MB15 Mg composite. The study, however, did not give details of the microstructural features of the composite reinforced with SiC particles. Studies of the mechanical properties revealed the UTS, 0.2% yield strength and elastic modulus of MB15 were evidently improved by the addition of TCP, while the ductility slightly decreased. The results indicated that TCP has a good strengthening effect on the MB15 matrix and was better than SiC particles on the same matrix. Table 2 shows the tensile properties of the unreinforced Mg-based alloy, TCP reinforced Mg composite and SiC reinforced Mg-based composite. It is observed from the table that the UTS values of the TCP/MB15 and SiCp/MB15 composite were within the same range, however the TCP/MB15 composite had slight reductions in ductility compared with the composite reinforced with SiC particles. The authors attributed increase in UTS and 0.2% yield strength of TCP/MB15 composite to hindrance to dislocation motion by the evenly distributed TCP, effective load transfer from the MB15 matrix to TCP and MB15 matrix grain refinement strengthening. The defects generated in the MB15 matrix and TCP during the processing were
considered responsible for decreased ductility in the MB15/TCp composite.

Xi et al. (2006) studied the performance of powder metallurgy processed ZK51 magnesium matrix composite reinforced with Ti–6Al–4V particulates (TAp). The microstructure of the composite showed uniform dispersion of the TAp, good interfacial bonding between the TAp and the ZK51 matrix and negligible TAp clustering. Results from mechanical testing showed that the UTS, 0.2% yield strength, Young’s modulus and linear work hardening markedly increased with the addition of TAp reinforcement to the matrix. However, the elongation to fracture decreased slightly in the TAp/ZK51 composite (from 8.5 to 5.6%). The study also evaluated these properties for the same alloy reinforced with a SiC reinforcement. Table 3, which presents a summary of the results of room temperature tensile tests of the materials studied, showed that the UTS and elongation to fracture were higher for the TAp reinforced composite compared with SiCp reinforced composites. Also noteworthy is the minimal ductility loss when comparing the reinforced composites with the unreinforced alloy. The increase in work hardening rate of the TAp/ZK51 composite was linked to factors such as: grain refinement; restriction of dislocation motion by TAp and interfaces; and the effective load transfer from ZK51 matrix to the TAp. The higher UTS of TAp/ZK51 composite was mainly ascribed to higher linear work hardening.

Umeda et al. (2010) studied the microstructure and mechanical properties of powder consolidated and solid-state sintered Ti particulate reinforced Mg composites. The compression strength of the Ti particle reinforced Mg composites increased slightly with an increase in Ti mass per cent but the tensile strength did not improve because of the weak Ti/α-Mg matrix interface bonding. The use of atomized Mg powder and Ti particles for the composite development, however, yielded improved tensile strength and elongation. This was linked to improved molten Mg and Ti particle wetting, which facilitates continuous interface bonding and strength, inevitably providing effective load transfer and Orowan strengthening. Figure 4(a) shows the stress–strain curve of the Mg-based composites developed using elemental mixtures of pure Mg and pure Ti, while Figure 4(b) shows the stress–strain curve of atomized pure Mg powder and Mg-Ti. The effect of atomization on the tensile properties of Mg-Ti composite is observed in the figures. Figure 4(a) shows only marginal improvements in mechanical properties between the unreinforced Mg and the composite, while obvious differences are observed in Figure 4(b).

Meenashisundaram and Gupta (2014) carried out an investigation to improve the mechanical properties of disintegrated melt deposition synthesized and hot deformation processed pure magnesium reinforced with 0.58, 0.97 and 1.98 vol.% nano-Ti particulates. The microstructures of the composites revealed fairly homogeneous dispersion of Ti nanoparticles, low porosity, and good Mg matrix and Ti nanoparticle interface integrity. The addition of different volume per cent of Ti nanoparticles to Mg matrix decreases the CTE of the Mg matrix, which marginally improved the dimensional stability of pure magnesium. Furthermore, there was significant grain refinement and hardness improvement in the Ti nanoparticle reinforced Mg composites studied. Also, the 0.2% yield strength and UTS of the Mg composites improved with the addition of Ti nanoparticulates as reinforcements. The study showed that the addition of 1.98 vol.% Ti nanoparticulates to pure Mg improved the 0.2% yield strength by ~112% and the UTS by ~80%, with a decrease in ductility of ~49%, which was still comparable to results obtained for other Mg-Ti composite systems reported in the literature. Table 4 gives a comparison of the mechanical properties of Mg alloys and Mg-based composites developed using different processing routes. It is observed that processing route

| Table 2. Tensile properties of the MB15 alloy and composites. |
|----------------|----------------|----------------|----------------|----------------|
| Materials      | State     | UTS (MPa) | 0.2% Yield strength (MPa) | Elongation to fracture (%) | Young’s modulus (GPa) |
| MB15 alloy     | Extruded | 283       | 202                      | 8.9                    | 45.5                  |
|                | Aged     | 315       | 229                      | 8.5                    | 46.2                  |
| TCp/MB15 alloy | Extruded | 352       | 278                      | 6.0                    | 51.6                  |
|                | Aged     | 386       | 295                      | 5.6                    | 52.8                  |
| SiCp/MB15 alloy|          | 355       | 302                      | 3.2                    | 57.0                  |

Table 3. Room temperature tensile test results for Mg alloys and ZKS1 reinforced composite.

| Materials | UTS (MPa) | 0.2% Yield strength (MPa) | Elongation to fracture (%) | Young’s modulus (GPa) | Linear work hardening rate |
|-----------|-----------|---------------------------|---------------------------|-----------------------|---------------------------|
| ZKS1 alloy| 315       | 229                       | 8.5                       | 46.2                  | 10.4                      |
| SiCp/ZKS1 | 355       | 302                       | 3.2                       | 57.0                  | 17.7                      |
| TAp/ZKS1  | 386       | 295                       | 5.6                       | 52.8                  | 16.9                      |

Source: adapted from Xi et al. (2005).

Source: adapted from Xi et al. (2006).
affects the tensile properties of Mg-based composite, and ductility increases have been recorded with the use of Ti as reinforcement to Mg matrices. The improvement in the strength of Mg-Ti nanocomposite when compared with pure Mg was postulated to be probably due to: (i) an increase in the dislocation density as a result of thermal expansion coefficient mismatch between Mg and Ti; (ii) the existence of uniformly distributed high hardness Ti nanoparticulates as reinforcement; (iii) Ti particle constrained dislocation movement; (iv) finer matrix grain size; (v) absence of Mg-based intermetallics; (vi) good Mg and Ti structural compatibility (both hexagonal close packed (HCP) structures); (vii) good Mg and Ti wettability; and (viii) high elastic modulus and yield strength of well-bonded and strong Ti nanoparticulates compared with magnesium. The test of the compressive properties of the Mg-Ti nanocomposite as reinforcement.
nanocomposites produced at room temperature revealed that 0.97 Ti additions increased the 0.2% compressive yield strength of Mg by ~59% and 0.58 Ti additions increased the ultimate compressive strength of Mg by ~34% with a slight decrease in the ductility.

Rashad et al. (2015) studied the mechanical and work hardening behaviour of semi-powder metallurgy and hot extrusion processed Mg-based composites reinforced with 10% Ti and 10% Ti-1% Al particulates. The microstructural characterization revealed that Ti and Al micrometre-sized particulates refined the grain structure of the composites in comparison with pure Mg matrix. Also, the reinforcements (Ti and Al) were evenly dispersed in the matrix, and this was associated with the composites’ processing method. The Mg-10Ti and Mg-10Ti-1Al composites exhibited generally improved mechanical strength and ductility compared with monolithic Mg. The improved ductility of Mg-10Ti-1Al composite was attributed to the combined addition of Ti and Al particulates and the absence of intermetallic phases in the composites. The authors ascribed the increase in strength of the composites to the Hall–Petch effect due to refined grains, difference in CTE between reinforcement and matrix, and elastic modulus and hardness differences between Mg matrix and Ti particulate.

The studied works have somewhat justified the use of metallic reinforcements in Mg-based composites. The metallic reinforcements caused either a slight reduction or an improvement in the ductility of Mg composites. For metallic glasses, Ni and Cu reinforced Mg composites the ductility reduced slightly, and the reduction depended on the concentration of the reinforcements present. Ti reinforcements had a different reinforcing effect on Mg and Mg alloy matrices. The ductility of Mg-based composite reinforced with Ti and Ti-based alloys increased compared with other metallic and ceramic reinforcement types. Other studies have also been carried out on other possible reinforcement alternatives for Mg and its alloys.

2.2.2. Metallic glass reinforcement

We have previously discussed the properties of metallic glasses which make them suitable reinforcements for metal matrices. The following are reports on the use of metallic glass reinforcement for Mg and Mg alloy matrices. 

Dudina et al. (2009) developed a novel Mg91.4Al12.2Zn5.4Mn0.1 alloy matrix composite reinforced with 15 vol. % Vitraloy6 (Zr57Nb3Cu15.4Ni12.6Al10) metallic glass particles using induction heating and low-pressure sintering. A relatively even dispersion of the metallic glass particles in the matrix was observed in the composite’s microstructure. Also, it was observed that densification of the composite was successful, confirmed by the absence of porosities and interface reaction products. Uniaxial compression tests showed that the hardness, yield strength and fracture strength of the composite reinforced with metallic glass particles were higher compared with the unreinforced alloy (the high fracture strength reflects improved toughness of the composite). Also, there was no significant loss in ductility in the metallic glass reinforced Mg composites.

Sankaranarayanan et al. (2015) embarked on a study to assess the structural and mechanical properties of microwave sintered and hot extrusion processed Mg composites reinforced with Ni50Ti50 metallic glass particles. It was observed that Ni50Ti50 metallic glass particles were fairly well dispersed in the Mg matrix, which appeared relatively finer than the unreinforced Mg. This was attributed to the tendency of Ni50Ti50 metallic glass particles to act as preferential sites and facilitate grain nucleation within the parent matrix during hot extrusion. The microhardness measurements indicated that the Ni50-Ti50 metallic glass particles improved the pure Mg hardness, which was attributed to the matrix work hardening facilitated by the hard (~860 Hv) Ni50Ti50 particles. The compressive strength of the Mg/Ni50Ti50 composite was significantly enhanced with little consequence on the compressive ductility. There was also enhanced tensile strength of the Mg/Ni50Ti50 composites due to effective Mg matrix-to-Ni50Ti50 particle load transfer. The composites’ tensile ductility reduced with increasing Ni50Ti50 particles; though the values are comparable to that of many Mg MMCs. Summarily, the strength improvement in the composite was attributed to the following: load bearing capacity of Ni50Ti50 particles; thermal mismatch strain facilitated dislocation strengthening; and grain size strengthening.

2.2.3. Summary

Recent trends in the area of Mg composites have revealed that metallic reinforcements enhance the strength of Mg-based composites, however the ductility was not improved in the presence of most of these reinforcements. Exceptions were reported with the use of Ti as reinforcement, as appreciable increase in ductility was observed in all the studies reviewed. Metallic glasses were also presented as suitable reinforcements for Mg matrices, and their additions moderately improved ductility in Mg and Mg alloy matrices. A summary of the mechanical properties of Mg systems discussed in this section and the associated mechanisms for the respective observations is presented in Table 5.
### Table 5. Summary of the mechanical response of Mg matrix composites developed with metallic-based reinforcements.

| Matrix + reinforcement | Processing technique | Yield strength (MPa) | UTS (MPa) | Elongation (%) | Yield strength (MPa) | UCS (MPa) | Elongation (%) | Strengthening/toughening mechanisms |
|------------------------|----------------------|----------------------|-----------|----------------|---------------------|-----------|----------------|-------------------------------------|
| Mg + Ni 7.3%           | Disintegrated melt deposition technique coupled with hot extrusion | 337 ± 15 | 370 ± 14 | 4.8 ± 1.4 | 14% | 313 ± 29 | 0.7 ± 0.1 | Uniform distribution of reinforcements, presence of intermetallics |
| 14% (Hasan & Gupta, 2002b) | Disintegrated melt deposition technique coupled with hot extrusion | 281 ± 13 | 355 ± 15 | 2.5 ± 0.2 | Effective load transfer, presence of intermetallics |
| Mg + Cu 10%            | Disintegrated melt deposition technique coupled with hot extrusion | 355 ± 11 | 386 ± 3 | 1.5 ± 0.3 | Presence of secondary phases |
| 26% (Hasan & Gupta, 2003) | Disintegrated melt deposition technique coupled with hot extrusion | 435 ± 27 | 1.0 ± 0.1 | |
| Mg + Cu 3.59% (Ho et al., 2004) | Microwave assisted rapid sintering and hot extrusion | 188 ± 13 | 218 ± 11 | 5.9 ± 1.1 | Work hardening, thermal mismatch, Orowan strengthening, effective load transfer |
| 10% (Wong & Gupta, 2007) | Disintegrated melt deposition technique coupled with hot extrusion | 194 ± 17 | 221 ± 17 | 5.6 ± 1.2 | Orowan strengthening, effective load transfer |
| Mg + Ti 5.6%           | Disintegrated melt deposition technique coupled with hot extrusion | 163 ± 12 | 248 ± 9 | 11.1 ± 1.4 | Dislocation strengthening/Ti |
| 9.6% (Hasan & Gupta, 2003) | Disintegrated melt deposition technique coupled with hot extrusion | 154 ± 10 | 239 ± 5 | 9.5 ± 0.3 | Diffusion and elastic mismatch |
| Mg + Ti-Al 10% (Rashad et al., 2015) | Powder metallurgy | 180 (+6, 4) | 221 (+7, -9) | 16.1 (+1.5, -1.2) | | | | Synergistic effect of two ductile reinforcements (Ti and Al) |
| Mg + Ti-Al 10% (Rashad et al., 2015) | Powder metallurgy | 184 (+5, 8) | 224 (+9, -4) | 14.9 (+1.1, -1.0) | | | | |
| Mg + Ti 0.58%          | Disintegrated melt deposition technique coupled with hot extrusion | 134 ± 7 | 190 ± 7 | 6.3 ± 0.6 | 129 ± 2 | 431 ± 8 | 17.4 ± 0.3 | Dislocation strengthening, grain refinement, load bearing capacity of reinforcement |
| 0.9% (Meenashisundaram & Gupta, 2014) | Powder metallurgy | 179 (+6, -3) | 218 (+6, -6) | 15.5 (+1.4, -2.0) | | | | |
| Mg + Ti 1%             | Powder metallurgy | 278 | 352 | 6.0 | | | | |
| 3% (Umeda et al., 2010) | Powder metallurgy | 295 | 386 | 5.6 | | | | |
| Mg + Ti 10%            | Powder metallurgy | 147 | 212 | 11.1 | | | | |
| Mg + Al 10%            | Powder metallurgy | 163 | 238 | 21.2 | | | | |
| Mg + metallic glass    | Induction heating and low-pressure sintering | 325 | 542 | 10.5 | | | | |
| (Dudina et al., 2009) | Powder metallurgy | 94 ± 5 | 144 ± 6 | 8.8 ± 1.7 | 67 ± 9 | 291 ± 12 | 15.9 ± 0.7 | Dislocation strengthening, grain size strengthening |
| Mg + Ni50Ti50 3%       | Microwave sintering and hot extrusion | 127 ± 4 | 183 ± 6 | 6.5 ± 0.9 | 89 ± 3 | 368 ± 8 | 15.1 ± 1.5 | |
| Mg + Ni50Ti50 6%       | Hot extrusion | 148 ± 7 | 178 ± 9 | 2.0 ± 1.3 | 102 ± 4 | 417 ± 6 | 14.9 ± 2.0 | |
| Mg + Ni50Ti50 10%      | Hot extrusion | 148 ± 7 | 178 ± 9 | 2.0 ± 1.3 | 102 ± 4 | 417 ± 6 | 14.9 ± 2.0 | |
2.3. Copper base MMCs

Copper matrix composites are primarily developed using ceramic-based reinforcements (Sagar, Samir, & Amit, 2013; Sathiskumar, Murugan, Dinaharan, & Vijay, 2014), with selection largely influenced by their material properties, availability and cost consideration (Li et al., 2019; Salvo, Mangalaraja, Udayabashkar, Lopez, & Aguilar, 2019). However, Cu has been observed to exhibit very poor wetting for ceramic materials, which often results in poor interface bonding and adversely affects mechanical properties of Cu matrix composites (Kumari, Kumar, Sengupta, Dutta, & Mathur, 2014; Li, Zhang, Zhang, Che, & Wang, 2015). Hence, there have been efforts to address this limitation in Cu-based composites. Part of the strategies explored is the use of metallic and intermetallic additions to reinforce Cu matrices. There are, however, few studies which have ventured into the use of metallic and intermetallic additions for the purpose of reinforcing Cu matrices.

2.3.1. Metallic reinforcement

Alaneme and Odoni (2016) compared the mechanical behaviour of stir cast copper matrix composites reinforced with 5, 7.5 and 10 wt.% SMC with that reinforced with 10 wt.% alumina (Al₂O₃). The study showed that the hardness of the SMC reinforced Cu matrix composites was higher than that reinforced with 10 wt.% Al₂O₃. There was also improved UTS, per cent elongation and tensile toughness achieved with the use of 5 wt.% SMC as reinforcement in the Cu-based composite compared with the use of 10 wt.% Al₂O₃. The improved strength was linked to the strong Cu/SMC interface which facilitates stress redistribution from the Cu matrix to the stronger SMC that served as reinforcement. Also, the improved ductility achieved was associated with higher plastic strain sustaining capacity, which is significantly enhanced by the good Cu/SMC interface.

2.3.2. Metallic glass reinforcement

Cardinal et al. (2019) investigated the use of Ta particles having two different geometries as adequate reinforcement to improve the plasticity of Cu-Zr-Al bulk metallic glass matrix. Large irregular shaped Ta particles and fine spherical shaped Ta particles were introduced into the matrix in volume fractions ranging from 5 to 50% for different composite grades. The composite grades produced via spark plasma sintering consolidation were subsequently observed through optical and scanning electron microscopy to be well densified. However, larger magnifications revealed heterogeneous distribution of Ta particles in composite grades with higher volume fraction of Ta particles. Mechanical testing of the composites showed that the hardness decreases with increased addition of Ta particles (irrespective of particle size or geometry) while yield strength decreased as volume fraction of Ta particles exceeded 20%. As expected, increased plasticity accompanied decrease in yield strength, and the highest elongations were recorded for 50% volume fraction of Ta particles. Unfortunately, plastic deformation in composites with high volume fractions of the reinforcement immediately followed with significant damage due to the heterogeneous distribution of particles in these composites. Hence the authors established from their investigations that 30% volume fraction of Ta particulate was optimal for a good combination of hardness and plasticity in Cu-Zr-Al bulk metallic glass matrix. Figure 5 displays the extent of plastic deformation in Cu-based matrix reinforced with Ta particles.

2.3.3. High entropy alloy reinforcement

Chen et al. (2015) used an AlCoNiCrFe high entropy alloy (HEA) synthesized by mechanical alloying as reinforcement for a Cu matrix. The Cu matrix composites having 10 and 20 wt.% of the synthesized HEA were fabricated using powder metallurgy. Microscopic analysis of the produced composites revealed that there were no pores or intermetallic phases present in the microstructures, signifying compact sintering and the absence of interfacial reactions. Also, there was no grain growth during the fabrication of the composites, as revealed by an average grain size of 20 nm in the microstructures. The compression tests show that the AlCoNiCrFe reinforced Cu matrix composites had enhanced strength with increasing weight per cent of reinforcements, 160% increase for 10 wt.% and 220% for 20 wt.% additions, respectively. The ductility, however, decreased with this trend and the unreinforced sample had the best ductility of all the samples tested. The composite with 10 wt.% of AlCoNiCrFe had the best combination of strength and ductility.
since the ductility drop was not so significant compared with the unreinforced Cu.

2.3.4. Summary

This section has shown that sparse literature exists on the use of metallic reinforcements for Cu matrices, making it difficult for definite conclusions to be drawn on the effect of metallic reinforcement on the mechanical performance of Cu-based composites. The studies reviewed show that metallic reinforcements offer good interface bonding with the Cu matrix, which for optimally selected reinforcement weight per cent results in good combination of strength and ductility in the composites. Further research could still be carried out to assess the effect of other refractory metallic materials serving as reinforcements on the mechanical performance of Cu-based MMCs. Table 6 presents at a glance the Cu-based systems discussed.

2.4. Zn-Al-based base metal matrix composites

Zinc-based composites are a class of MMCs developed from Zn alloys, especially the ZA alloy series, which have many industrial applications. These composites were developed as alternatives to Zn alloys in several engineering and commercial applications where high temperature stability of material properties is required (Kumar, Sadashivappa, Prabhukumar, & Basavarajappa, 2006). These applications often require sliding wear resistance and dimensional stability, modest strength and toughness for effective service performance. Thus, a suitable reinforcement for Zn-based composites would be one which would enhance the aforementioned properties. Ceramics have been largely used to reinforce Zn-based composites, but the use of metallic and hybrid (metallic and ceramic) reinforcements has been explored with a view to achieving improved properties and performance.

2.4.1. Metallic reinforcement

Alaneme et al. (2016) compared the mechanical behaviour of stir cast Zn27Al composites reinforced with 5, 7.5 and 10 wt.% SMC with that reinforced with 5 wt.% Al2O3. It was observed that the hardness and UTS of the ZA27Al alloy reinforced with SMC were higher than that reinforced with 5 wt.% Al2O3. The hardness was noted to increase with increase in SMC weight per cent while the reverse was recorded with respect to tensile strength behaviour. The reduction in strength with increase in SMC weight per cent was held to be due to a higher tendency for chip agglomeration above 5 wt.% SMC, which results in reduced strength. The Zn27Al reinforced with 5 wt.% SMC also recorded the highest per cent elongation and fracture toughness of all the composite compositions developed, the 5 wt.% Al2O3 reinforced composition included. The improved fracture toughness and ductility observed in the Zn27Al reinforced with 5 wt.% SMC compared with that reinforced with 5 wt.% Al2O3 is linked to the inherent toughness and ductility of SMC coupled with the good Zn27Al matrix/SMC interface.

There have also been efforts to assess the mechanical properties and performance of Zn-based composites with the use of metallic and ceramic reinforcements as hybrid reinforcement.

2.4.2. Summary

Available studies on the use of alternative reinforcements in ZA-based matrices are still in the early stages and thus few reports exist to make concrete conclusions on their effectiveness as reinforcements in ZA-based composites. Table 7 shows a summary of the properties presented in the discussed work.

3. Summary and future scope

This review has elucidated the role of metallic reinforcements in the mechanical behaviour of different metal matrices with the focus on ductility and toughness, which are quite low in ceramic reinforced MMCs. For Al matrices, it was observed that Fe, Ni, SMC, V, Ta and metallic glasses, which are chiefly utilized as metallic reinforcement, result in generally improved mechanical properties with ductility levels slightly superior to that of the ceramic reinforced AMCs but lower than that of the unreinforced Al matrix.
The progress on the use of alternative reinforcements for Mg and alloys is slightly different from what has been obtained with Al composites. Metallic reinforcements such as Cu and Ni preserve considerably the ductility (slight or minimal reduction) in Mg composites, but this has been successful at lower concentrations of these reinforcements. The most significant success recorded thus far in ductility improvement in MMCs using metallic reinforcements was obtained with the use of selected metallic glasses and in Ti and Ti alloy reinforced Mg-based composites. The other metallic matrices Cu and Zn-Al which are of engineering importance discussed in this review at present have limited research on the use of metallic reinforcements for enhancement of ductility and toughness, thus it is difficult for far-reaching conclusions to be drawn based on the few works available.

There are few important observations worth documenting on the suitability or otherwise of metallics as reinforcements in MMCs. Based on the results from the several works discussed in this review, metallic materials can be considered to be good technical substitutes for conventional ceramic reinforcements in metal matrices. However, the composite processing technique is an important consideration which was overlooked by most investigations reported. The composite development and processing routes explored in most of the studies were powder metallurgy, extrusion and disintegrated melt deposition, with very few adopting conventional liquid metallurgy techniques which are more versatile, cheaper and very amenable for the development of MMCs. The debate will still be on as to the reliability of metallic materials as reinforcement in MMCs. While their promise remains indisputable, outright replacement of ceramic reinforced with metallic materials may be constrained by the sort of processing suitable for their development and by the type of metallic matrix and areas of application.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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### Table 7. Summary of the mechanical response of Zn matrix composites developed with metallic-based reinforcements.

| Matrix reinforcement | Processing technique | Tensile | Compressive | Strengthening/ | Elongation (%) | Strengthing/|
|----------------------|----------------------|---------|-------------|----------------|----------------|----------------|
| Zn + Steel chips 5%  | Double stir casting   | 190 ± 5 | 6.5 ± 0.5   | Good interface | bond           |                 |
|                      |                      | 160 ± 3 | 5 ± 0.4     |                 |                 |                 |
| Zn + Steel chips 7.5%|                      | 145 ± 3 | 4.5 ± 0.4   |                 |                 |                 |
| Zn + Steel chips 10% |                      |         |             |                 |                 |                 |

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