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MAGNESIUM METAL MATRIX COMPOSITES - A REVIEW

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Abstract. Magnesium matrix composites are potential materials for various applications of aerospace and defence organisations due to their low density, good mechanical and physical properties. The improvement of specific strength, stiffness, damping behaviour, wear behaviour, creep and fatigue properties are significantly influenced by the addition of reinforcing elements into the metallic matrix compared with the conventional engineering materials. This paper presents the overview on the effects of different reinforcements in magnesium and its alloy, highlighting their merits and demerits. The major phenomenon like interfacial transition, agglomerating effect, fibber-matrix bonding and the problems associated with the particle distribution are discussed in this paper. Effect of reinforcement on the microstructure and mechanical properties like tensile strength, yield strength, ductility, strain, hardness, wear and fatigue are also discussed in detail. Major applications of different magnesium MMCs are also analysed critically in this work.

1. INTRODUCTION

Metal–matrix composites (MMCs) are finding increasing applications in many of today's industries. In particular, Magnesium and its alloys have gained widespread attention in scientific research as well as commercial application as energy conservation and performance demands are increasing because of their low density, approximately two-third of that of aluminium, and high specific strength as compared to other structural metals. These properties are important in automotive and aerospace applications in order to reduce fuel consumption and to reduce green house emission [1-3]. However, the application of magnesium alloys is limited evidently due to their poor creep resistance at high temperatures, low strength, low modulus and wear resistance [4,5]. Therefore, Reinforcements are needed to improve the properties of the base metal. MMCs fabricated from magnesium would provide attractive alternatives to Al MMCs. As a lightest metal structural material, magnesium matrix composites exhibit many advantages over monolithic magnesium or magnesium alloys, such as high elastic modulus, high strength, superior creep and wear resistances at elevated temperatures. However, their ductility was reduced, which limits their widespread application [6,7]. The desired properties can be achieved by a judicious selection of the type and size of the reinforcing particles. The reinforcements should be stable in the given working temperature and also non-reactive too. The most commonly used reinforcements are Silicon Carbide (SiC), Aluminium Oxide (Al_2O_3), and Titanium Carbide (TiC), etc. SiC reinforcement increases the ultimate tensile strength, yield strength, hardness, ductility and wear resistance of Mg and its alloys [8]. The particle distribution plays a significant role in the mechanical properties of the Magnesium MMC, which is improved by intensive shearing. TiC particulates play a vital role on damping behaviour of magnesium composite and it's alloy. Reinforcement of TiC particles lead in improvement of yield strength tensile strength and elastic modulus significantly, while the ductility is reduced to some extent. The reinforce-

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ment of Al_2O_3 induces good creep resistance, compressive strength. Creep strengthening occurs due to the effective load transfer between plastic flow in the matrix and fibbers [9].The reinforcement of CNTs leads to improvement of the wettability, bonding strength and tensile strength of Magnesium matrix composites. Nevertheless, the addition of CNTs may result in weakening the basal plane texture [10]. Boron Carbide is one of known hardest element. It has high elastic modulus and fracture toughness. The addition of Boron Carbide (B_4C) in magnesium matrix increases the interfacial bonding strength, flexural strength of hybrid composite, hardness and wear resistance [11-13]. Fibers are the most important class of reinforcements which affect on the directional strength and stability of the composites. They transfer the strength to the matrix constituent influencing and enhancing their properties as desired. However, Particulate reinforced magnesium matrix composites could be produced by many different methods, such as powder metallurgy, stir casting, and spray deposition techniques etc. [14]. Numerous studies had been made on magnesium matrix composites. This paper examines the various factors like (a) effect of various reinforcement (b) mechanical properties like strength, Damping behaviour, wear, fatigue behaviour, etc. (c) processing technique and its effects.(d) applications of the speciality magnesium matrix composite were discussed.

2. SILICON CARBIDE REINFORCED MAGNESIUM MMC

C.Y.H. Lim et al. [15] investigated the wear behaviour of magnesium (Mg)-based metal–matrix composites (MMCs) reinforced with silicon carbide particulates (SiCp) during dry sliding. The composites exhibit slightly superior wear resistance under the lower load, but the effects of the SiC particulate reinforcements on wear resistance are not as conclusive under higher load. During SEM analysis, it was observed that the melt wear becomes the dominant wear mechanism, causing gross deformation of the magnesium matrix at the contacting interface. The useful range of Mg/SiCp composites appears to be limited to loads and speeds below 30 N and 5.0 m/s respectively. K.K. Deng et al. [16] evaluated the microstructure and mechanical properties of a particulate reinforced magnesium matrix composites at elevated temperature with a 50% reduction in height. The texture of the forged composites was measured by neutron diffraction. A strong basal plane texture formed during forging, and the intensity of basal plane texture weakened as the forging temperatures increased. The particle distribution was significantly improved by hot forging. X.J. Wang et al. [17] investigated the Influences of extrusion parameters on microstructure and mechanical properties of SiCp/AZ91 composites. Extrusion was done at different extrusion temperatures and ratios. The mechanical properties of the composites were improved with the increase of extrusion temperatures and ratios. Particle distribution was improved. As extrusion temperatures and ratios increased, the grain sizes of matrix were also increased. Particle redistribution and particle cracking was significantly affected the mechanical properties of the extruded composites. Zainuddin Sajuri et al. [18] evaluated the microstructure and mechanical properties of SiC reinforced magnesium composites prepared by spark plasma sintering technology. It was found that the sintering temperatures of 585 °C and 552 °C were the most suitable sintering temperatures for the magnesium and the AZ31 alloy respectively. The mechanical properties i.e. hardness and tensile strength increased with increasing of SiC content up to 10 wt.%. Further increase of SiC content gives rise to the tensile strength decreas due to the agglomeration of SiC particles. The agglomeration of SiC particles was found to lead to the degradation of the interfacial bonding strength between matrix and reinforcement. K.B. Nie et al. [19] investigated the effect of hot extrusion on microstructures and mechanical properties of SiC nanoparticles reinforced magnesium matrix composites. Extrusion of the SiCp/AZ91 nanocomposites induced large-scale dynamic recrystallization resulting in a fine matrix microstructure. The ultimate tensile strength, yield strength and elongation to fracture of the SiCp/AZ91 nano composites were simultaneously improved by extrusion. The tensile strength and ductility value increases in comparison to the unreinforced and extruded AZ91 alloy. K.K. Deng et al. [20] fabricated the AZ91 magnesium matrix composites reinforced with submicron-SiC particulates (0.2 μm) along with six volume fractions (0.5, 1, 1.5, 2, 3, and 5 vol.%). Microstructure characterization of the composites showed significant grain refinement, relative uniform reinforcement distribution, and presence of minimal porosity. A strong basal plane texture was formed in both AZ91alloy and SiCp/AZ91 composites during extrusion. Addition of submicron- SiC particulates results in weakening of the basal plane texture but simultaneously it improves the yield strength, micro-hardness, thermal stability, and elastic modulus. K.B. Nie et al. [21] investigated the mechanical properties and microstructure of SiC nano-particles reinforced magnesium matrix composites, which was fabricated by ultrasonic vibration. The mechanical properties can be significantly improved and the strength and elongation to fracture of the nanocomposites are simultaneously enhanced. The grain size of the matrix in the SiCp/AZ91 nanocomposite decreases. The ultimate tensile strength, yield strength and elongation to fracture of the SiCp/AZ91 nano-composite were simultaneously enhanced in comparison to that of the AZ91 alloy. The interface study between the matrix and SiC nanoparticles in the nanocomposite implies that SiC nanoparticles bonded well with the matrix without interfacial activity. X.J. Wang et al. [22] investigated the effect of particle size on microstructure and mechanical properties of SiCp/AZ91 magnesium matrix composite. Composites with lower volume fraction of submicron SiCp particles (2%) had significant influence on grain refinement and strengthening effect. As the volume fraction increased to 5% and 10%, mechanical properties reduced due to agglomerated submicron SiC particles. The strengthening effect was enhanced with the increasing of volume fraction. K.B. Nie et al. [23] conducted a study on microstructure and tensile properties of SiC-micro particles reinforced magnesium matrix composites. The addition of the micro-SiC particles results in decrease of the grain size of matrix. While most of the phase $Mg_{17}Al_{12}$ varied from coarse plates to lamellar precipitates in 3 vol.% SiCp/AZ91 composites. The interface study suggested that micro-SiC particles bonded well with the alloy matrix without interfacial reaction. The ultimate tensile strength and yield strength were improved at 3 vol.% while elongation to fracture was almost kept constant. M.J. Shen et al. [24] investigated the effect of bimodal size SiC particulates on microstructure and mechanical properties of AZ31B magnesium matrix composites after hot extrusion. The microstructure investigation shows that bimodal size SiC particles have a significant effect on the microstructure and mechanical property of the AZ31B matrix alloy. The ultimate tensile strength and yield strength of bimodal size SiCp reinforced magnesium matrix composite were enhanced compared with monolithic AZ31B matrix alloy and single size SiCp reinforced magnesium matrix composites. X.J. Wang et al. [25] conducted a study on the novel stir casting assisted by ultrasonic treatment processing of micro-SiC particles reinforced magnesium matrix composites. The ultrasonic treatment significantly improved the mechanical properties of the composites fabricated by different parameters compared with traditional stir casting. Addition of SiC particles results in refinement of the grain size. Grain sizes of composites decreased with the increases of particle contents. The ultimate tensile strength, yield strength and elastic modulus were significantly enhanced as the particle contents increased. Wang Zhao-hui et al. [26] fabricated a magnesium matrix composite reinforced with SiC nanoparticles by ultrasonic method. The micro structural evaluation indicates that the nanoparticles can be dispersed into magnesium alloys uniformly and efficiently with the aid of ultrasonic vibration. The grains of composites were refined and the mechanical properties of composites were significantly improved in comparison to matrix alloy. The SiC nanoparticles can act as the heterogeneous nucleation of α-Mg. Hu Lianxi and Wang Erde [27] fabricated SiCw/ZK51A magnesium matrix composite by a modified two-step squeeze casting technique. The new fabrication technique revealed that it was increasing the modulus and mechanical strength significantly as compared with the unreinforced matrix alloy. There was no interfacial reaction in the SiCw: ZK51A composite, attesting that SiC whiskers are very stable reinforcements for magnesium matrix composites. Bimodal sized (Micro-particles: m and Nano-particles: n) SiC particulates (SiCp) reinforced magnesium matrix composites with different volume fractions of micro-particles were studied by M.J. Shen et al. [28]. The distribution of bimodal size SiCp and the mechanical properties of the AZ31B alloy were significantly improved after hot extrusion. The ultimate tensile strength the yield strength of the AZ31B/SiC/1n+14p composite are stronger compared to AZ31B/SiC/1n+4p andAZ31B/SiC/1n+9p composites at 1 vol.% volume fraction of nano SiCp. The elongation to fracture was decreased comparing with the AZ31B /SiC /1n+4p and AZ31B/SiC/ 1n+9p composites. K.B. Nie et al. [29] also conducted a study on the microstructure of a magnesium matrix composite reinforced with submicron particles of SiCp at room temperature deformation. A stepped tensile method was adopted to observe the development of microstructure at different tensile strain state. The TEM study showed that the existence of submicron SiC particles could promote the dislocation multiplication as well as impede dislocation motion. Dislocation density increased with the increase of tensile strain. The strength of the composite increases due to the movement of the submicron SiC particles of grain and twin boundaries. The interface study revealed that single submicron SiC particle bonded well with the matrix alloy after tensile process. G. Garcés et al. [30] studied the influence of the presence of ceramic particles on the twinning mechanism in magnesium matrix composites using synchrotron radiation diffraction. The tensile twining process was used to control the plasticity of extruded composites. The volume fraction of twins is rapidly saturated as the volume fraction of reinforcement increases. Shanshan Zhou et al. [31] investigated the effects of different volume ratios on the microstructure and mechanical properties of SiCp/AZ91 magnesium matrix composite. The results revealed that the submicron SiCp is more conducive to grain refinement as compared with micron SiCp. The average grain size decreases and the submicron particle dense region increases with the increase of volume ratio. The yield strength of bimodal size composite is higher in comparison to the monolithic micron composite. With the increase of volume ratio, the interface debonding weakens and the amount of dimples increases. Y.Q. Wang et al. [32] investigated the effect of SiC particles on micro arc oxidation process of magnesium matrix composites. The corrosion resistance of MAO coating was also investigated. Results showed that the integrality and electrical insulation properties of the barrier film on the composites were destroyed by the SiC particles. The growth efficiency of the MAO coating decreased with the increase in the volume fraction of SiC particles. The corrosion current density of SiCp/AZ91 MMCs was reduced by two orders of magnitude after MAO treatment. However, the corrosion resistances of the coated composites were lower than that of the coated alloy. Wenbin Xue et al.[33] investigated the corrosion resistant ceramic coatings up to 80 μm thick were fabricated on SiCP/AZ31 magnesium matrix composite by micro arc oxidation (MAO) technique in Na_3PO_4+KOH+NaF solution. The thicker coating is compact and exposed a good adhesion to the composite substrate. The SEM and EDX analysis showed a few residual SiC phases that has been found in the coatings. The corrosion resistance of the SiCP/AZ31 composite was significantly improved by MAO surface treatment. However, the corrosion resistance of coated composite was also depending on the coating thickness. Shruti Tiwari et al. [34] conducted a study on the corrosion behaviour of SiC reinforced Mg- matrix composites. Corrosion resistance decreased with increasing SiC volume fraction. The corrosion behaviour of the composite did not significantly influenced by the galvanic corrosion. Electrochemical impedance spectroscopy indicated that the higher corrosion rates for the composites could be related to the defective nature of surface film. R. Arrabal et al. [35] investigated the corrosion behaviour of silicate plasma electrolytic oxidation coating magnesium matrix composite. The experiment was done by alternating current (AC) plasma electrolytic oxidation (PEO) in humid and saline environments. It has been found that corrosion attack started around the Al–Mn inclusions and gradually developed into general corrosion without significant galvanic coupling between the matrix and the SiCp for untreated composites. The result showed that the hardness and corrosion resistance increases with proportion of reinforcement increasing. Pit formation and hydration of the outer layer were the main mechanisms of corrosion of PEO-treated specimens.

3. TITANIUM CARBIDE REINFORCED MAGNESIUM MMC

Y.L. Xi et al. [36] investigated the mechanical properties of a Ti–6Al–4V particulate (TAp) reinforced magnesium matrix composite. It was observed that the tensile strength of the composite significantly improved compared to the unreinforced magnesium alloy. The Ti–6Al–4V particulate found to be more beneficial for the ductility of magnesium matrix composites than SiC particles. The ultimate tensile strength, 0.2% yield strength and elastic modulus of ZK51 were remarkably increased, while the ductility was decreased to some extent. Zhang Xiuqing et al. [37] investigated the mechanical properties and damping behaviour of TiC particulates reinforced magnesium matrix composites. The results revealed that the TiC particulates play a vital role on damping capacity and mechanical properties of the composites. Tensile strength and damping capacity of the composites were improved compared to AZ91 magnesium alloy. The damping characterization was explained with twinning, dislocation motion, grain boundary slip and interface slip. Wei Cao et al. [38] conducted a study on the damping behaviour and In situ synthesis of TiC reinforced magnesium matrix composites. It was found that, with the increase of reinforcement percentage, damping capacity of the magnesium alloy increased. The dislocation damping mechanism is an attributed to Improved damping capacities of composites. Interface damping has become a new contributor to the increase of damping capacity at elevated temperatures. Q. Dong et al. [39] fabricated and characterised the TiCp reinforced magnesium matrix composites by in situ reactive infiltration process. They found that the smaller elemental particle size and a processing temperature above 973K were beneficial to synthesizing of TiCp reinforced magnesium matrix composites for (Tip + Cp)/Mg system. Zhang Xiuqing et al. [40]

characterised the damping behaviour of 8 wt.% TiC reinforced Magnesium matrix composites. They have found that the damping capacity of materials is independent of frequency while it is depending on strain and temperature. Two damping peaks have been observed in damping–strain curve at a temperature of 130 °C and 240 °C, respectively. The former was due to dislocation motion and the latter was due to interface and grain boundary sliding. Damping capacity of magnesium matrix composites is generally higher due to the addition of TiC particulates than that of AZ91 magnesium alloy. Q.C. Jiang and his co-researchers [41] conducted a study to implementation of TiC–Al master alloy processed via self-propagating high-temperature synthesis reaction in a TiC particulate reinforced magnesium matrix composite. The results revealed that the PRMMC have higher properties (such as hardness, UTS, and wear resistance) compared to those of the unreinforced magnesium alloy. M. Balakrishnan et al. [42] conducted an experiment to synthesize AZ31/TiC magnesium matrix composites using FSP and investigated the microstructure using scanning electron microscopy. Four different volume fraction of TiC particles (0, 6, 12, and 18 vol.%) were taken. The SEM analysis indicated that TiC particles were uniformly distributed in the magnesium matrix without any Clusters formation. There was no interfacial reaction between the magnesium matrix and the TiC particle. X.Y. Gu et al. [43] investigated the microstructure and mechanical properties of transient liquid phase (TLP) bonded TiC reinforced magnesium metal matrix composite (TiCP/AZ91D) joints using aluminium interlayer. The concentration of Al in the joint centreline decreased with the increase in bonding time at a temperature of 460 °C. The joint microstructure also changed from α-Mg solid solution, AlMg and $Al_{12}Mg_{17}$ compounds to α-Mg, $Al_{12}Mg_{17}$ at this temperature. The increase of $Al_{12}Mg_{17}$ compound and aggregation of TiC particulates were the main reason for affecting the mechanical properties of joints. The joint shear strength of above 58 MPa was obtained at the bonding temperature of 460 °C or 480 °C for the bonding time of 20 min. Babak Anasori et al.[44] reported on the mechanical properties of Mg matrix composites fabricated by pressure less melt infiltration of Mg and Mg alloys into porous performs of TiC and Ti_2AlC. Pure Mg with three different Mg alloys – AZ31, AZ61andAZ91 at a loading of 50-vol.% was used. It was observed that the ultimate compressive strength, hardness, elastic moduli and yield strength enhanced with the increase of Al content. At 1028±5 MPa, the ultimate compressive strength of aTiC–AZ61composite was almost 40% higher at a TiC particle size distribution is Lorentzian and cantered at, *dc*=0.41±0.01 μm compared to the same composite with coarser TiC particles with a bimodal size distribution centred with *dc*=1.6±0.1 μm, and 5.8±0.3 μm. In case of Ti_2AlC composites, the best properties were obtained when AZ61 was reinforced with Ti_2AlC particles with *dc*=0.51±0.01 mm.

4. ALUMINIUM OXIDE REINFORCED MAGNESIUM MMC

V. Sklenicka et al. [45] conducted a study on constant stress tensile creep behaviour of an Al_2O_3 reinforced AZ91 magnesium based composite with 20 vol.%. The creep resistance of the reinforced material was considerably improved in comparison to the matrix alloy. The creep strengthening arises due to the effective load transfer between plastic flow in the matrix and fibers. TEM study revealed better fiber–matrix interface bonding during creep exposure. Due to the enrichment of Al in the matrix near to the alumina fibers, precipitation of the $Mg_{17}(Al, Zn)_{12}$ phase enhanced which was promoted by heterogeneous nucleation. S. Jayalakshmi et al. [46] investigated the tensile behaviour of AM100 magnesium alloy and its composites at different temperatures. The nature and distribution of precipitates influenced the inherent brittle nature of AM100 alloy and it dominates the tensile behaviour. At higher temperatures, the strength was attributed to the load carrying capacity of the fibres. The strength reduction is mainly due to averaging and softening of the matrix alloy, which indicates the addition to matrix flow properties. A. Bakkar and V. Neubert [47] investigated the the corrosion behaviour of Al_2O_3 fibres strengthened magnesium AS41 composite, in aqueous solutions containing various concentrations of NaCl at different pH values was studied and compared with the behaviour of pure AS41 magnesium matrix alloy. They observed that the corrosion resistance reduces at higher chloride concentrations. There was no presence of galvanic corrosion between the fibres and matrix. The presence of higher aluminium zones around the fibers could result from the interfacial reactions, showed higher corrosion resistance compared to the original matrix. Henry Cay et al. [48] fabricated and characterised the porous alumina-reinforced magnesium composites. The results exhibited that the average pore sizes increased by 25 μm, 70 μm, and 100 μm for the samples with 10%, 28%, and 38% porosities respectively. The mechanical properties revealed that, (i) with a steep increase of stress, an initial regime deformed elastically along the linear line, a long and intermediate regime, and a densification regime. (ii)The composites possessed lower density and higher yield strength compared to cast dense magnesium. (iii) Young's modulus and average yield strength were anisotropic. Dehong Lu et al. [49] studied the friction and wear behaviour of nano-alumina (n-Al_2O_3) particles reinforced and CNTs reinforced magnesium matrix composites with different volume fractions (0.3%CNTs, 0.1%Al_2O_3+0.2% CNTs, 0.15% Al_2O_3+0.15% CNTs, 0.2%Al_2O_3+0.1% CNTs and 0.3% Al_2O_3). They found that all the composites have more wear resistance compared with FSP AZ31 alloy. The wear resistant of n-Al_2O_3 reinforced composite is lower when compared to CNTs independently reinforced composite. At a load of higher than1.95 MPa, the wear of (0.1%Al_2O_3+0.2%CNTs)/AZ31 hybrid composites were significantly lower compared to those of other composites. The friction coefficient was also lower. M. Srinivasan et al. [50] investigated the feasibility of joining of alumina reinforced AZ31B magnesium nanocomposites solid-state welding process. It was found that with the increase of friction pressure and forging pressure, the joint efficiency increased. Joint efficiency decreased with the increase of friction time. P.P. Bhingole et al. [51] synthesized an AZ91 alloy matrix composites by in situ reactive formation of hard MgO and Al_2O_3 particles with addition of magnesium nitrate to the molten alloy. Formation of hard oxide due to in situ chemical reactions leads to increasing the ultimate strength, hardness and strain-hardening exponent of the composites. The sliding wear resistance of the composites improved because of the presence of well-dispersed hard oxide particles and stronger interface that obtained from cavitations- enhanced wetting of reactively formed particles. Q.B. Nguyen et al. [52] investigated the wear behaviour of AZ31B/nano- Al_2O_3 composite, magnesium alloy, AZ31B, and its nano-composites using a pin-on-disk setup against a steel disk counterface under different sliding speeds(1, 3, 5, 7 and 10 m/s) for different normal load (10 N, and 1, 3, and 5 m/s for 30 N). The results showed that over the sliding speed range for both normal loads the wear rate of the composite reduced gradually but at low speed the wear rate of the composite was higher compared to the alloy.

5. CNT REINFORCED MAGNESIUM MMC

Yongha Park et al. [53] investigated the mechanical properties of silicon coated multi walled CNTs reinforced AZ91 metal matrix composites. The results revealed that a homogeneous microstructure was formed and the performance of the composite was improved due to the way for the formation of Si coated carbon nanotubes. The Si coated MWNTs leads to improvement in the distribution, wettability, bonding strength and tensile strength in the MWNTs matrix composites. S.J. Yoo et al. [54] suggested a new method for the fabrication of CNT-reinforced magnesium composites by using accumulative roll bonding to magnesium sheets coated with ball-milled Al–CNT powders. The results obtained that CNTs are uniformly distributed in the matrix. A small addition of CNT improved in the mechanical properties of the composites significantly. C.D. Li et al. [55] carried out an experiment through the fabrication of CNTs reinforced magnesium matrix composites by an improved process. It was extruded at 350^{0}C with an extrusion ratio of 20:1. The addition of CNTs could result in weakening the basal plane texture. The presence of CNTs evidently improved the ultimate tensile strength, Young's modulus and yield strength of the extruded composites. Load transfer mechanism, grain refinement and Orowan strengthening mechanism play important roles on the increase of the yield strength. High strengthening efficiency of CNTs was obtained in the composite fabricated by their process. Harun Mindivan et al. [56] fabricated and analysed the microstructure and corrosion behaviour of 6 wt.% Al with 0.5, 1, 2, and 4 wt.% nanosized CNTs reinforced magnesium composites by mechanical ball milling, cold pressing and hot extrusion process without sintering step. The microstructure analysis revealed that with increase of CNT content, the uniform distribution of CNTs at the chip surface decreased. Corrosion test showed that a small addition of CNTs (0.5 wt.%) evidently improved the hardness and corrosion resistance compared with base alloy. While there were significant decrease of compression strength, hardness, wear rate and corrosion resistance with the increase in the CNT weight fraction in the initial mixture. R. Schaller et al. [57] conducted a study on multiwalled carbon nanotubes reinforced magnesium composite prepared by powder metallurgy and then charged with hydrogen by annealing at 620K under a pressure of 0.4 MPa. Two relaxation peaks were observed at 190K and 330K (frequency 6 kHz).the height of the peaks increases strongly with hydrogen charging. These peaks might be interpreted by atomic relaxation due to hydrogen in the Mg_2Ni phase. With degassing under vacuum at 750K, the height of both the peaks decreased significantly. X.J. Wang et al. [58] investigated the influence of CNTs on microstructure and strengthening mechanism of Mg–6Zn matrix composites. The results revealed that the most CNTs distributed uniformly and individually in the composites, and good interfacial bonding was achieved. CNTs significantly improved the ultimate tensile strength (UTS), yield strength (YS) and Youngs modulus and refined the grains size of Mg–6Zn matrix. C.D. Li et al. [59] approached a successful development to fabricate bulk carbon nanotubes (CNTs) reinforced Mg matrix composites. The CNTs distribution in the composites was influenced by the solidification rate. At a lower solidification rate, CNTs were pushed ahead of the solidification front and will cluster along grain boundaries. Good interfacial bonding had been achieved at high solidification rate. The ultimate tensile strength (UTS) and yield strength (YS) of the composite were significantly improved compared with matrix alloy. The mechanical properties of the composite are better at higher solidification rate. Moreover, Kelly–Tyson formula agreed well with the experimental tensile value at higher solidification rate. Xiaomin Yuan et al. [60] conducted a study on micro structural characterization of MWCNTs reinforced magnesium alloy composites fabricated by powder compact laser sintering. At a laser, output power is 500 W; the composites were sintered thoroughly due to fully dense and uniform cross-sectional microstructures and revealed high micro hardness, grain refinement compared with monolithic AZ91D. MWCNTs increased the laser absorption of the MWCNTs/AZ91D composites compare with monolithic AZ91D, which produced high temperature and cooling rate to make the composites tough. Mui Hoon Nai et al. [61] highlighted the use of a metallic coating of nanoscale thickness on carbon nanotube for enhancing the interfacial characteristics in CNTs reinforced magnesium (Mg) composites. It was found that the clustering adversely affects the bonding of pristine CNTs with Mg particles. The presence of nickel coating on the CNT leads to the formation of Mg2Ni intermetallics at the interface that improved the adhesion between Mg/Ni–CNT particulates. The presence of grain size refinement and improved dispersion of the Ni–CNT reinforcements in the Mg matrix were also observed, which results in the micro-hardness, ultimate tensile strength and 0.2% yield strength was enhanced simultaneously by 41%, 39%, and 64% respectively for the Mg/Ni–CNT composites.

6. BORON CARBIDE REINFORCED MAGNESIUM MMC

Q.C. Jiang et al. [62] fabricated the B_4C particulate reinforced Magnesium metal matrix composites with different volume fractions (10, 15, and 20 vol. % B_4C). Characterization of Microstructure revealed that necklace distribution of B_4C particulates in the matrix. XRD analysis showed the formation of MgO and MgB_2 in B_4C/Mg composites. Hardness and wear resistance of the composites were significantly increased with increasing of B_4C particulates from 10 to 20 vol.%. Jianguo Li et al. [63] investigated the effect of $Mg_2B_2O_5$w and B_4Cp hybrid reinforcements on magnesium matrix composites. There was remarkably enhancement of flexural properties of the composites with the addition of $Mg_2B_2O_5$w and B_4Cp. Flexural strength of the hybrid composite is 29% higher in comparison to singular composite because of higher dislocation density in the matrix of the hybrid composite. The fracture behaviour revealed that most of $Mg_2B_2O_5$w and B_4Cp fracture in the matrix which suggests that the interfacial bonding strength between the matrix and reinforcements is relatively strong. Yantao Yao and Liqing Chen [64] proposed a new method for processing of B_4C particulate-reinforced magnesium-matrix composites. In metal melt infiltration composite fabrication process, there is a need to improve the wettability of the metal melt with ceramic perform. They have added a small amount of metal powder with higher melting point to the ceramic preform such that the surface tension of the Mg melt and the liquid-solid interfacial tension could be reduced. They found that boron carbide particulate-reinforced magnesium-matrix composites were successfully fabricated where Ti powder immiscible with magnesium melt was introduced into B_4C preform as infiltration inducer.

7. FIBER REINFORCED MAGNESIUM MMC

Bin Hu et al. [65] studied the Interface and fracture behaviour of short-fibers reinforced AE44 based Magnesium matrix composites fabricated by infiltration with molten AE44 (Mg–4.0Al–4.1RE–0.3Mn) alloy. Fracture initiation and growth was observed by in situ scanning electron microscopy. It was found that the distribution of the alloying elements was influenced by the fibers addition. During infiltration The SiO_2 binder reacted with molten magnesium and produced MgO. The Al–RE phases formed lamella ($Al_{11}RE_3$) on the surface of fiber and particle (Al_2RE) on the surface of matrix. Micro crack initiation has observed at the interface of the composite. Interfacial debonding, fiber breakage depending on the fiber distribution to the tensile stress direction. Xuezhi Zhang et al. [66] investigated the tensile behaviour of Magnesium AM60 based metal matrix composites (MMCs) reinforced with alumina (Al_2O_3) fibre at a pressure of 90 MPa. Tensile properties of unreinforced AM60 alloy, Al_2O_3 fibre/AM60 alloy and hybrid composite were investigated. The results showed that with the addition of fibers the tensile properties improved significantly but the ductility was reduced comparison to the unreinforced matrix alloy. Localized damages, like fibers damage and cracking, matrix fracture, and interface debonding were consistent with the tensile property. Jun TIAN and Zi-qiong SHI [67] studied the Creep behaviour of aluminium silicate short-fibre-reinforced magnesium matrix composite by the constant stress tensile creep test method. By varying the temperatures and stresses, they found that both the matrix and fibre have the same true stress exponent and true activation energy for creep. The composites creep behaviour is mainly controlled by controlling of the viscous slip of dislocation and the controlling of grain boundary slippage as a supplement.

8. CONCLUSION

Several confronts must be surmounted in order to strengthen the engineering usage of Magnesium matrix composites like fabrication processes, influence of reinforcement, effect of reinforcement on the microstructure and mechanical properties and its corresponding applications. The major conclusions derived from the prior works carried out can be summarised as following:

(a) SiC particle reinforced Magnesium MMCs have higher wear and creep resistance compared to Al_2O_3 reinforced Magnesium MMCs.

(b) The wear resistance of Al_2O_3 independently reinforced magnesium matrix composite is higher than that of the CNTs independently reinforced magnesium MMCs.

(c) Reinforcement of CNTs in the matrix of magnesium and its alloy improved the wetability and bonding strength of the composites.

(d) Sliding wear resistance of Magnesium MMCs is better as compared to that of the base alloy. As the amount of reinforcement increased, the MMCs became more wear resistant. AZ91-6.5-UST shows highest wear resistance among all the Magnesium MMCs.

(e) Dense B_4C/Mg composites with homogeneously distributed B_4C particles within the magnesium matrix was processed by a processing condition at 993K for 120 minute with 6 vol.% or above of metal powder Ti is added into B_4C ceramic preform.

(f) It has been found that the addition of Boron Carbide (B_4C) in magnesium matrix increases the interfacial bonding strength, flexural strength of hybrid composite.

(g) The addition of fibers in magnesium matrix composite the tensile strength is improved but the ductility are reduced.

(h) Application of ultrasonic vibrations to the melt magnesium MMCs increases the uniformity of particle distribution, avoided agglomeration, and decreased porosity in the castings.

(i) The creep behaviour of magnesium MMCs is controlled by the creep of its matrix, which is mainly the controlling of viscous slip of dislocation and the controlling of grain boundary slippage as a supplement.

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