

Review Article

Sandeep Kumar Khatkar*

Hybrid magnesium matrix composites: A review of reinforcement philosophies, mechanical and tribological characteristics

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Abstract: Magnesium hybrid composites are a new class of lightweight metal matrix composites having excellent physical, mechanical, wear and corrosive properties. Hybrid magnesium matrix composites are fabricated using different combinations of reinforcements having basic properties like wear resistance and high strength of ceramics, self-lubricating of graphite, MoS₂, CNT, and graphene, high thermal conductivity of carbon, diamond, and cubic boron nitride, and low cost of fly ash. This article presents an overview of different combinations of reinforcements used for fabrication of hybrid magnesium matrix composites and their effects on the mechanical and tribological properties of the hybrid materials. The major issues like agglomeration, interfacial phenomena, reinforcement–matrix bonding, and problems related to uniform distribution of particles are discussed in this article. Magnesium hybrid composites have the potential of satisfying the recent demands of aerospace, automobile, biomedical, defense, marine, and electronics industries. The future directions and potential research areas in the field of magnesium hybrid composites are also highlighted.

Keywords: magnesium hybrid composites, solid lubricants, characterization of metal matrix composites, lightweight materials

1 Introduction

Concerns about better fuel economy and environmental emission reduction have promoted efforts to increase

applications of lightweight materials in current engineering applications, especially in automobiles. In recent years, magnesium and its composites have found major applications in the field of automobile, aerospace, electronics, and defense industries due to their low density and high specific strength, which can lead to a reduction in fuel consumption and greenhouse emission [1–3]. For example, in a V6, 3 liter cylinder car, replacing cast iron and aluminum engine block with magnesium results in a reduction of 54.6 and 9 kg, respectively, which further promotes fuel savings and emission reduction [1]. Particularly, in the automobile industry, magnesium-based metal matrix composites (MMCs) are attractive materials for the construction of pistons, brakes rotors, cylinder bores, cylinder liners, car door frames, and steering wheels due to their specific modulus, stiffness, good damping capacities, and wear and dent resistance [2]. The potential application of magnesium hybrid composites is presented in Figure 1.

In spite of attractive range of mechanical properties of magnesium and its alloys, relatively poor creep resistance at high temperature, low modulus, low strength, low wear resistance, and limited room temperature ductility are the serious impediment against their wider applications [3,4]. Considering the survey of different published articles during composing this article, it was discovered that three approaches have been adopted in order to exploit the potential of magnesium and improve in the performance of its MMCs.

- The first approach involves a reduction in the size of reinforcement from micro- to nano-level [3].
- The second approach was finding low-cost and easily available industrial wastes like fly ash as alternative reinforcing materials to overcome the high cost of ceramics and their limited supply in developing countries; however, these composites show inferior properties than synthetic reinforced MMCs [5–8].
- And the third approach was developing a new class of MMCs reinforced with two or more reinforcements, known as hybrid MMCs. Hybrid magnesium composite

* Corresponding author: Sandeep Kumar Khatkar, Department of Mechanical Engineering, State Institute of Engineering and Technology (SIET), Nilokheri, Haryana 132117, India, e-mail: sandeepkhatkar99@gmail.com

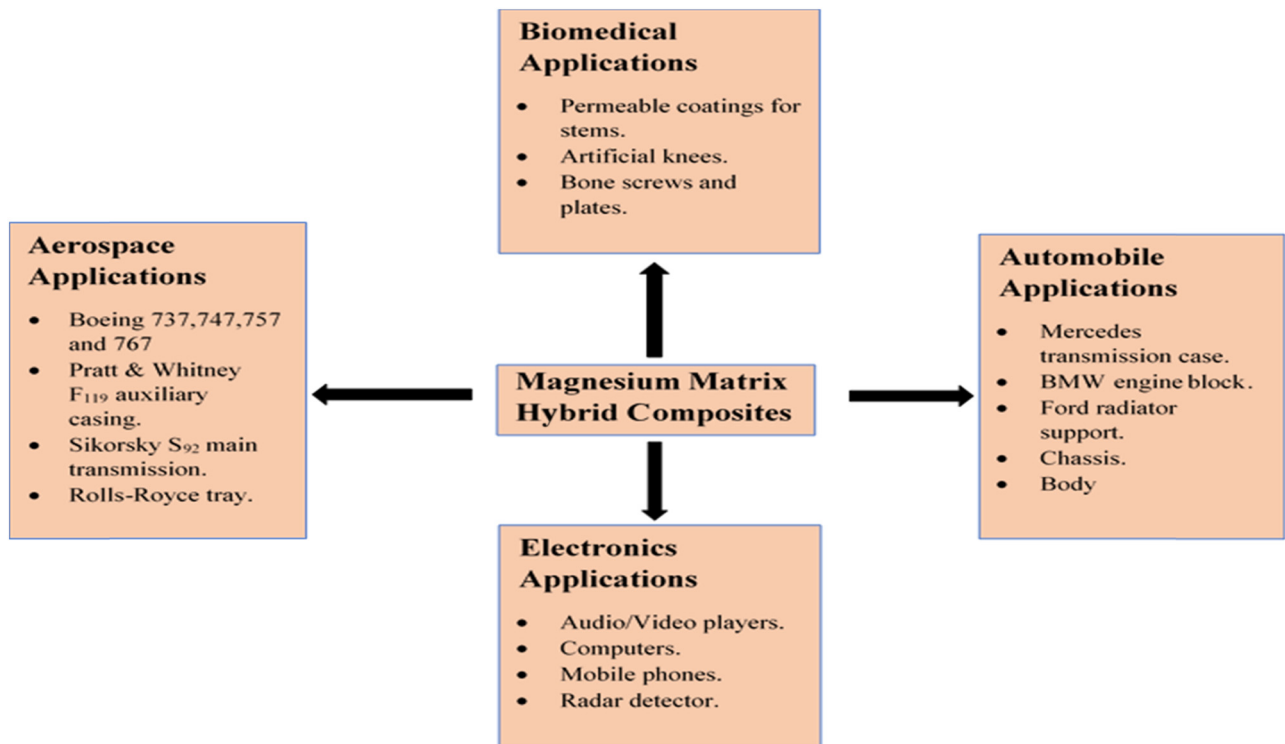


Figure 1: Potential applications of magnesium hybrid composites.

materials give room for the possible reduction of cost coupled with property optimization by reinforcing low-cost materials as secondary reinforcements. Along with the problem of the high cost of ceramics, the limited supply of ceramics materials in developing countries also motivates the fabrication of composite materials by using multiple reinforcements [9].

Some researchers have reported comparable or improved mechanical and tribological behavior of hybrid magnesium composites than that of monolithic magnesium composites even at reduced processing costs [10,11]. In hybrid magnesium composites, the reinforcements of different physical and chemical properties are combined to achieve the optimization of material properties. The most commonly used reinforcement includes the following: a) non-continuous ceramic reinforcements are silicon carbide (SiC), cerium oxide, aluminum oxide (Al_2O_3), yttrium oxide (Y_2O_3), boron carbide (B_4C), and titanium carbide; b) self-lubricating solid lubricants such as CNT, MoS_2 , graphite, and graphene; and c) metals like copper (Cu), silicon (Si), and titanium [11,12]. The percentage contribution of different reinforcements for fabricating hybrid magnesium composites reviewed in this article is illustrated in Figure 2. SiC (30%) has been reported as the most reinforced ceramic particles followed by Al_2O_3 (20%) due to its wettability in magnesium. SiC reinforcement increases mechanical

properties such as ultimate tensile strength, yield strength, hardness, ductility, and wear resistance of magnesium alloys and its composites. SiC particle-reinforced magnesium composites have higher wear and creep resistance than that of Al_2O_3 -reinforced magnesium composites [4]. TiC, a hard refractory metallic material, has fine wettability in magnesium, and TiB_2 has a coherent crystal lattice with magnesium [13]. The reinforcement of hybrid TiC and TiB_2 in magnesium alloy AZ91 significantly improves the hardness, wear resistance, 0.2% YS, ultimate tensile strength (UTS), failure strain, and work of fracture of alloy, while reduces the ductility to some extent [14,15]. TiC plays an important role on damping behavior of magnesium and its alloys, moreover; in situ formed TiC reinforcement enhances tensile strength of magnesium alloy AZ91D (especially at higher temperatures) [16]. The ceramic Al_2O_3 improves the corrosion resistance, compressive strength and creep resistance of magnesium and its alloys [17], moreover; reinforcement of Al_2O_3 dissolves the $\text{Mg}_{17}\text{Al}_{12}$ intermetallic phases in magnesium alloys, which leads to improvement in fracture strain values [18,19].

Enhancement in tribological and mechanical properties was achieved by fabricating green or environmental friendly self lubricating hybrid magnesium composites, where ceramic particles were reinforced keeping in mind of high strength and solid lubricants such as CNT, MoS_2 ,

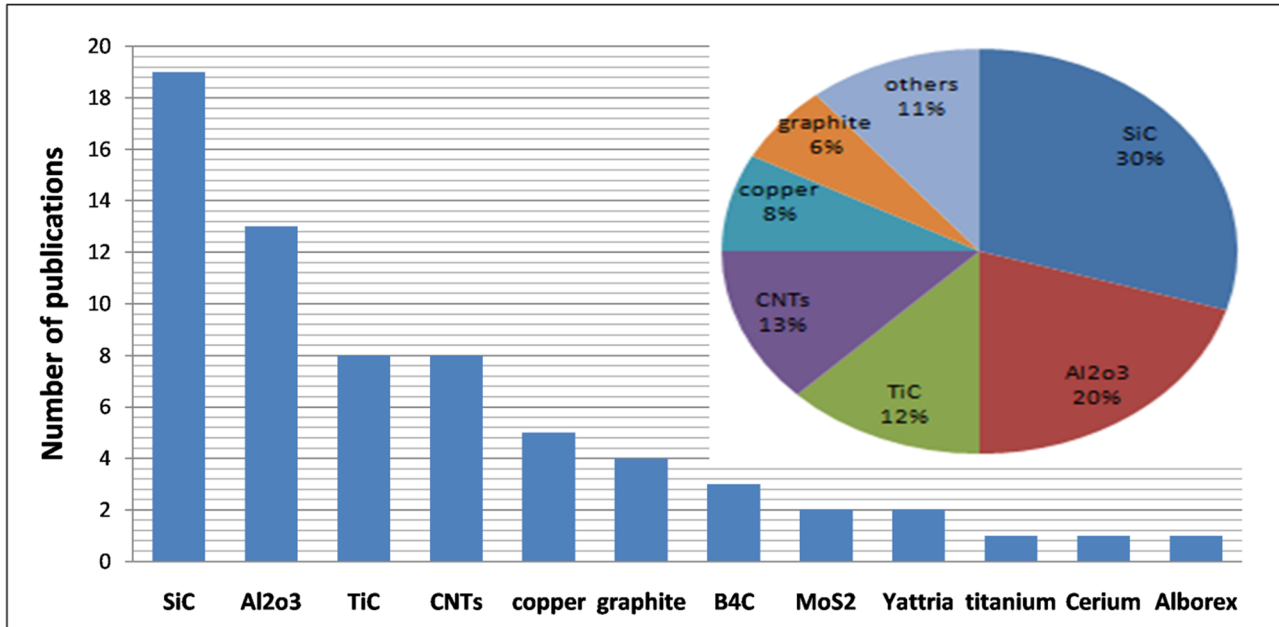


Figure 2: Percentage contribution of different reinforcements for fabrication of magnesium-based MMHC's reviewed in this article.

graphite and graphene was impregnated as secondary reinforcement for their self lubrication behavior [20–22]. SiC and short carbon fibers (SCF) hybrid reinforcement considerably improves the creep resistance of AZ91 magnesium alloy [23]. Increased copperized hybrid nano-reinforcement (i.e. $0.7Y_2O_3 + 0.3Cu$) enhances the formability of pure magnesium even at higher temperature up to $100^\circ C$ [24]. Boron carbide is one of the known hardest elements. It has high elastic modulus and fracture toughness. The reinforcement of Boron Carbide (B_4C) leads to improvement of the interfacial bonding strength, flexural strength, hardness, and wear resistance of magnesium-based MMCs [25,26]. The improvement in physical, mechanical, and microstructural properties of magnesium-based MMCs has been observed due to strengthening provided by various ceramics materials. The strengthening mechanisms observed for ceramic-reinforced magnesium hybrid composites are illustrated in Figure 3.

The addition of CNT in magnesium increases the wettability, bonding strength, and tensile strength [4]. Nevertheless, increasing CNTs content in CNT/SiCp/AZ91 hybrid composites significantly decreases the coefficient of thermal expansion (CTE) as CNTs possessed near-zero thermal expansion [27]. Moreover; the researchers are also exploring the biological properties of the CNTs-reinforced magnesium hybrid composites for biomedical applications [28–30]. Abzari et al. [31] fabricated magnesium MMCs by encapsulated CNT particles using semi powder metallurgy technique and studied their effect on

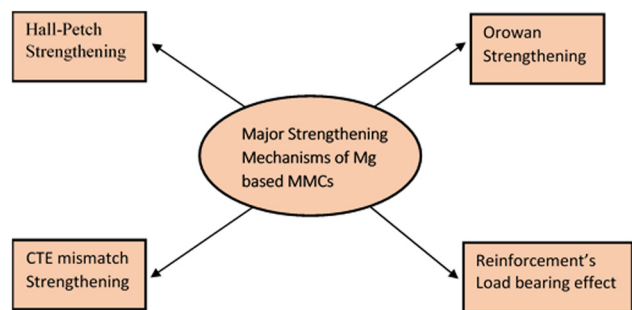


Figure 3: Strengthening mechanisms for ceramics-reinforced magnesium hybrid composites.

the mechanical and biological properties of fabricated nano-MMCs. It was found that CNT reinforcements resulted in exceptional mechanical as well as biological properties.

Various techniques have been developed and applied for fabrication of hybrid magnesium composites such as powder metallurgy, disintegrated melt deposition metal (DMD) technique, stir casting, squeeze casting, remelting and dilution technique, infiltration method, friction stir processing, and in-situ formation of reinforcement in the matrix [32]. The percentage contributions of these different techniques used by earlier researchers in this review are illustrated in Figure 4. Powder metallurgy (36%) has been reported as the most contributing fabrication technique followed by squeeze casting (23%) for hybrid magnesium composites. Powder metallurgy is an

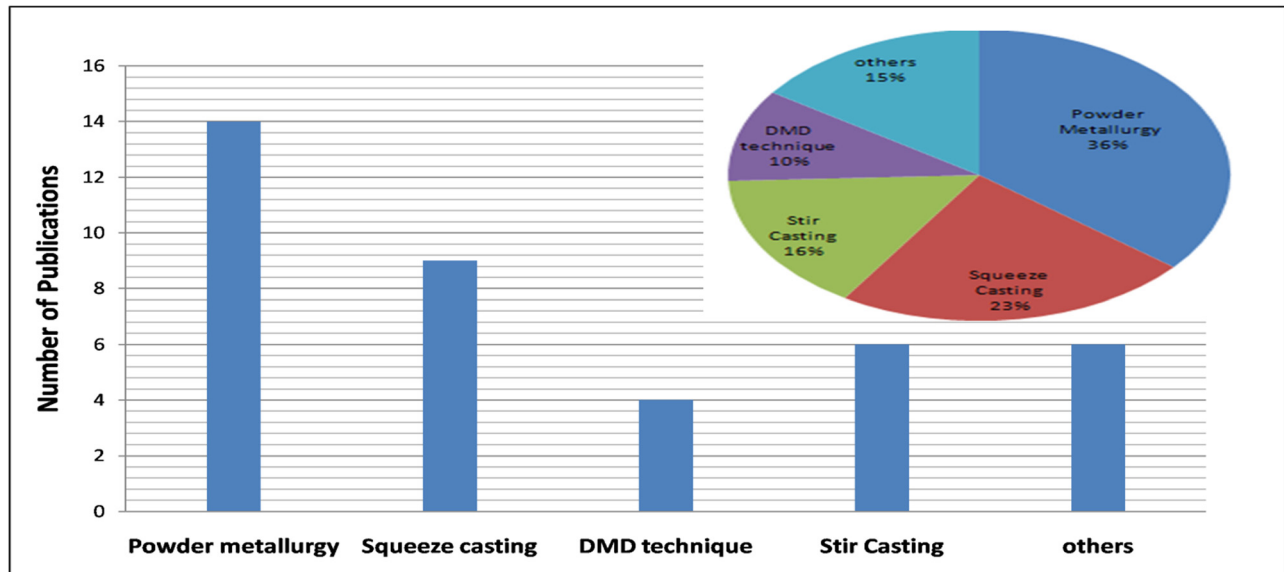


Figure 4: Percentage contribution of different fabrication techniques for magnesium-based MMCs reviewed in this article.

important solid-state processing technique having the following tremendous advantages: (i) nano-sized reinforcements can be uniformly distributed; (ii) avoid particle clustering, agglomeration, wettability, and formation of unwanted secondary phases which is common during liquid-state processing; (iii) hybrid composites with higher reinforcement content can be successfully fabricated [3,11,26].

The primary objective of this article is to highlight the various factors like (a) the effect of various reinforcements and their combination; (b) mechanical, physical, and tribological properties like density, tensile strength, hardness, UTS, wear loss, and failure strain summarized in Table 1; (c) fabrication techniques and their effects; and (d) applications of hybrid magnesium composites.

2 Silicon carbide-reinforced hybrid magnesium composites

Prakash et al. [10] reported the mechanical and tribological properties of Mg–SiC composites, Mg–Gr composites, and Mg–SiC–Gr hybrid composites fabricated via powder metallurgy route and examined the influence of reinforcements, sliding distance, sliding speed and applied load on wear loss and COF of these composites. The results revealed that magnesium reinforced with SiC increases microhardness, COF, density, and wear resistance due to the inherent hard ceramic nature of SiC. The solid lubricant graphite was further added for lowering COF and increasing wear resistance by forming a lubricant layer between sliding

counterparts due to the soft and lubricative nature of graphite. However, further increase in the content of graphite above 5 wt%, reduced microhardness and wear resistance were due to increment of delamination and brittle fracture. Mg–10SiC–5Gr hybrid composites showed superior wear resistance among developed composites.

Thakur et al. [33] developed and characterized Mg/CNT nanocomposite and Mg/CNT/SiC nanocomposites. The hybrid composites were fabricated using powder metallurgy. The reinforcement of nano-sized SiC and CNT particles in pure magnesium results in lower CTE, higher microhardness, 0.2%Y.S, and UTS, while decreasing failure strain. Mg/0.3%CNT/0.7%SiC hybrid composite exhibited superior values of CTE, UTS, 0.2%Y.S, and microhardness among developed composites. The addition of SiC has a greater effect than CNT for improvement in mechanical and thermomechanical properties of fabricated hybrid composites, which is due to better resistance developed by SiC particles in matrix expansion than that of CNTs and poor CNTs/Mg bonding.

Rudajeva et al. [34] studied the effect of temperature on the thermal properties of QE22/SiCp/Al₂O₃ fiber hybrid magnesium composite with variation in temperature from 20 to 375°C. The hybrid composites were produced by the squeeze cast technique. The results revealed that reinforcing SiC particles and Al₂O₃ short fibers into QE22 magnesium alloy reduced the thermal diffusivity and thermal conductivity at any temperature. However, coefficient of thermal expansion (CTE) of QE22/SiCp/Al₂O₃ fiber hybrid magnesium composite was increased with an increment in temperature up to 286°C and beyond 286°C

Table 1: The mechanical and tribological properties of magnesium metal matrix hybrid composites

Composition	Processing technique	Density ($\text{g}\cdot\text{cm}^{-3}$)	Tensile/yield strength ($\text{N}\cdot\text{mm}^{-2}$)	UTS ($\text{N}\cdot\text{mm}^{-2}$)	Hardness	Wear loss (g)	Failure strain (%)	Ref.
Pure Mg	Powder metallurgy	1.7365 ± 0.0011	136 ± 8	170 ± 7	46 ± 3 HV	—	6.1 ± 1.0	[3]
Mg–5.6Ti	Powder metallurgy	1.7951 ± 0.0019	151 ± 4	190 ± 4	50 ± 3 HV	—	4.2 ± 0.3	
Mg–3Cu	Powder metallurgy	1.9635 ± 0.0014	188 ± 3	218 ± 7	59 ± 4 HV	—	5.9 ± 0.4	
Mg–5.6Ti–3Cu	Powder metallurgy	2.0971 ± 0.0061	197 ± 4	225 ± 2	64 ± 3 HV	—	2.6 ± 0.3	
Mg–(5.6Ti + 3Cu)BM	Powder metallurgy	2.1047 ± 0.0034	223 ± 4	253 ± 4	69 ± 1 HV	—	4.2 ± 0.6	
Mg	Powder metallurgy	1.737 ± 0.002	111.9 ± 7.7	155.8 ± 2.1	41 HV	—	5.9 ± 1.2	[8]
Mg–0.3CNT–0.7SiC	Powder metallurgy	1.742 ± 0.003	152.9 ± 4.1	195.4 ± 4.7	46 HV	—	3.3 ± 0.7	
Mg–0.5CNT–0.5SiC	Powder metallurgy	1.740 ± 0.001	152.1 ± 1.2	188.5 ± 2.7	45 HV	—	2.3 ± 0.6	
Mg–0.7CNT–0.3SiC	Powder metallurgy	1.739 ± 0.002	139.5 ± 6.5	182.9 ± 7.5	44 HV	—	2.1 ± 0.5	
Mg–1CNT	Powder metallurgy	1.736 ± 0.002	117 ± 6.2	153.8 ± 2.8	43 HV	—	1.5 ± 0.3	
AZ91	As-received alloy	—	—	—	—	—	—	[11]
AZ91–1SiC–1Gr	Vortex method	—	—	—	62.8 HV	0.0045	—	
AZ91–2SiC–2Gr	Vortex method	—	—	—	64.3 HV	0.0041	—	
AZ91–3SiC–3Gr	Vortex method	—	—	—	66.2 HV	0.0037	—	
Pure Mg	Powder metallurgy	1.7345 ± 0.0017	119.39 ± 7.63	169.22 ± 4.40	39.08 ± 0.8	—	5.47 ± 1.57	[16]
Mg–1SiC	Powder metallurgy	1.7414 ± 0.0007	131.14 ± 12.33	182.40 ± 9.43	43.08 ± 0.71	—	5.01 ± 0.46	
Mg–0.5SiC–0.5Al ₂ O ₃	Powder metallurgy	1.7410 ± 0.0006	155.66 ± 6.99	197.38 ± 1.83	46.12 ± 0.94	—	4.58 ± 2.08	
Mg–0.3–SiC–0.7Al ₂ O ₃	Powder metallurgy	1.7407 ± 0.0009	164.91 ± 1.43	206.10 ± 5.28	47.96 ± 0.57	—	4.47 ± 1.78	
Mg–10GNF–Alumina	Infiltration method	—	240	—	142 HV	—	—	[42]
Mg–15GNF–alumina	Infiltration method	—	238	—	136 HV	—	—	
Mg–20GNF–alumina	Infiltration method	—	233	—	120 HV	—	—	
Pure Mg	DMD technique	1.7129 ± 0.0015	125 ± 9	169 ± 11	48 ± 1 HV	—	6.2 ± 0.7	[27]
Mg–(5.6Ti + 2.5Al ₂ O ₃)	DMD technique	1.6755 ± 0.0255	175 ± 4	227 ± 10	74 ± 2 HV	—	3.3 ± 0.2	
Mg–(5.6Ti + 0.5Al ₂ O ₃)BM	DMD technique	1.7826 ± 0.0173	168 ± 8	214 ± 8	69 ± 1 HV	—	6.8 ± 0.8	
AZ31–1.5Al ₂ O ₃ –0.2SiC	Powder metallurgy	—	166 ± 3.8	269 ± 3.1	68 HV	—	16.90 ± 1.6	[23]
AZ31–1.5Al ₂ O ₃ –0.5SiC	Powder metallurgy	—	198 ± 4.1	293 ± 5.0	78 HV	—	10.58 ± 2.0	
AZ31–1.5Al ₂ O ₃ –1.0SiC	Powder metallurgy	—	208 ± 3.8	306 ± 3.8	91 HV	—	07.54 ± 1.8	
Mg	Powder metallurgy	1.65	—	—	29 HV	0.0091	—	[6]
Mg–5TiC	Powder metallurgy	1.8	—	—	55 HV	0.0072	—	
Mg–10TiC	Powder metallurgy	1.96	—	—	91 HV	0.0059	—	
Mg–5MoS ₂	Powder metallurgy	1.81	—	—	35 HV	0.0074	—	
Mg–10MoS ₂	Powder metallurgy	1.97	—	—	37 HV	0.008	—	
Mg–5TiC–5MoS ₂	Powder metallurgy	1.96	—	—	59 HV	0.0058	—	
Mg–5TiC–10MoS ₂	Powder metallurgy	2.12	—	—	53 HV	0.0075	—	
Mg–10TiC–5MoS ₂	Powder metallurgy	2.11	—	—	97 HV	0.0054	—	
Mg–10TiC–10MoS ₂	Powder metallurgy	2.27	—	—	89 HV	0.0061	—	
As cast base (ACB)	Stir casting	—	81	155	66 HV	—	6.5	[34]
As cast composite (ACC)	Stir casting	—	127	190	72 HV	—	6	
Homogenized ACB	Stir casting	—	83	201	73 HV	—	13	

(Continued)

Table 1: Continued

Composition	Processing technique	Density ($\text{g}\cdot\text{cm}^{-3}$)	Tensile/yield strength ($\text{N}\cdot\text{mm}^{-2}$)	UTS ($\text{N}\cdot\text{mm}^{-2}$)	Hardness	Wear loss (g)	Failure strain (%)	Ref.
Homogenized ACC	Stir casting	—	131	231	76 HV	—	12	
AZ91	RAD technique	1.81	82 $\pm$ 3	233 $\pm$ 0	—	—	6.0 $\pm$ 0.5	[36]
AZ91-(TiB ₂ + TiC)	RAD technique	1.93	95 $\pm$ 2	298 $\pm$ 2	—	—	2.4 $\pm$ 0.4	
Mg	Powder metallurgy	1.7379 $\pm$ 0.0050	93 $\pm$ 01	153 $\pm$ 07	40 $\pm$ 2 HV	—	7.9 $\pm$ 3.4	[37]
Mg-0.50Al-0.18CNT	Powder metallurgy	1.7346 $\pm$ 0.0070	116 $\pm$ 11	186 $\pm$ 12	50 $\pm$ 4 HV	—	10.9 $\pm$ 3.5	
Mg-1.00Al-0.18CNT	Powder metallurgy	1.7359 $\pm$ 0.0150	128 $\pm$ 12	208 $\pm$ 08	58 $\pm$ 3 HV	—	11.2 $\pm$ 2.9	
Mg-1.50Al-0.18CNT	Powder metallurgy	1.7370 $\pm$ 0.0300	156 $\pm$ 13	223 $\pm$ 12	60 $\pm$ 4 HV	—	7.0 $\pm$ 0.5	
AZ91D	As-received alloy	1.8091	62.1	—	20.5 BHN	0.017	0.36	[42]
AZ91D-1.5B ₄ C	Stir casting	1.8197	99.2	—	27.1 BHN	0.014	0.37	
AZ91D-1.5B ₄ C-1.5 Gr	Stir casting	1.8249	86.3	—	22.5 BHN	0.013	0.38	
Pure Mg	DMD technique	—	120 $\pm$ 9	169 $\pm$ 11	48 $\pm$ 1 HV	—	6.2 $\pm$ 0.7	[43]
Mg-5.6Ti	DMD technique	—	158 $\pm$ 6	226 $\pm$ 6	71 $\pm$ 2 HV	—	8.0 $\pm$ 1.5	
Mg-(5.6Ti + 0.5B ₄ C)BM	DMD technique	—	156 $\pm$ 9	228 $\pm$ 12	70 $\pm$ 4 HV	—	11.7 $\pm$ 0.4	
Mg-(5.6Ti + 1.5B ₄ C)BM	DMD technique	—	180 $\pm$ 5	238 $\pm$ 6	87 $\pm$ 5 HV	—	9.8 $\pm$ 0.7	
Mg	Powder metallurgy	1.738 $\pm$ 0.007	134	193	—	—	6.9	[45]
Mg-(0.7Y ₂ O ₃ + 0.0Cu)	Powder metallurgy	—	157	244	—	—	8.6	
Mg-(0.7Y ₂ O ₃ + 0.3Cu)	Powder metallurgy	1.775 $\pm$ 0.001	215	270	—	—	11.1	
Mg-(0.7Y ₂ O ₃ + 0.6Cu)	Powder metallurgy	1.792 $\pm$ 0.004	179	231	—	—	11.1	
Mg-(0.7Y ₂ O ₃ + 1.0Cu)	Powder metallurgy	1.825 $\pm$ 0.002	148	200	—	—	10.2	
Mg	Powder metallurgy	1.7360 $\pm$ 0.003	121 $\pm$ 5	179 $\pm$ 6	40 $\pm$ 1 HV	—	11.4 $\pm$ 1.1	[47]
Mg-(1Al ₂ O ₃ + 0.1Cu)	Powder metallurgy	1.766 $\pm$ 0.001	169 $\pm$ 11	205 $\pm$ 11	49 $\pm$ 2 HV	—	2.8 $\pm$ 0.4	
Mg-(1Al ₂ O ₃ + 0.3Cu)	Powder metallurgy	1.776 $\pm$ 0.001	190 $\pm$ 13	225 $\pm$ 13	56 $\pm$ 2 HV	—	4.1 $\pm$ 0.6	
Mg-(1Al ₂ O ₃ + 0.6Cu)	Powder metallurgy	1.793 $\pm$ 0.002	184 $\pm$ 7	224 $\pm$ 8	68 $\pm$ 2 HV	—	9.5 $\pm$ 1.2	
Mg-(1Al ₂ O ₃ + 0.9Cu)	Powder metallurgy	1.821 $\pm$ 0.001	202 $\pm$ 7	232 $\pm$ 7	59 $\pm$ 2 HV	—	4.10 $\pm$ 0.3	
Pure Mg	DMD Technique	1.7397 $\pm$ 0.0015	125 $\pm$ 9	169 $\pm$ 11	48 $\pm$ 1 HV	—	6.2 $\pm$ 0.7	[48]
Mg-Ti	DMD Technique	1.8002 $\pm$ 0.0017	158 $\pm$ 6	226 $\pm$ 6	71 $\pm$ 2 HV	—	8.0 $\pm$ 1.5	
Mg-Cu	DMD Technique	1.9681 $\pm$ 0.0010	182 $\pm$ 4	220 $\pm$ 4	82 $\pm$ 4 HV	—	8.9 $\pm$ 0.9	
Mg-Ti-Cu	DMD Technique	2.1089 $\pm$ 0.0019	196 $\pm$ 9	227 $\pm$ 4	86 $\pm$ 2 HV	—	5.7 $\pm$ 1.6	
Mg-(Ti + Cu)BM	DMD Technique	2.1096 $\pm$ 0.0016	201 $\pm$ 7	265 $\pm$ 11	91 $\pm$ 3 HV	—	7.5 $\pm$ 0.8	
Mg	As-received Mg	1.65	—	—	29 HV	0.009	—	[5]
Mg-5SiC	Powder metallurgy	1.75	—	—	50 HV	0.0077	—	
Mg-10SiC	Powder metallurgy	1.85	—	—	80 HV	0.0062	—	
Mg-5Gr	Powder metallurgy	1.73	—	—	28 HV	0.0081	—	
Mg-10Gr	Powder metallurgy	1.75	—	—	22 HV	0.0084	—	
Mg-5SiC-5Gr	Powder metallurgy	1.79	—	—	49 HV	0.0059	—	
Mg-5SiC-10Gr	Powder metallurgy	1.82	—	—	47 HV	0.0081	—	
Mg-10SiC-5Gr	Powder metallurgy	1.84	—	—	78 HV	0.0055	—	
Mg-10SiC-10Gr	Powder metallurgy	1.87	—	—	70 HV	0.0064	—	

*DMD denotes disintegrated melt deposition; RAD stands for remelting and dilution.

CTE was decreased. The kind and volume fraction of reinforcement influenced the thermal diffusivity and thermal conductivity of the hybrid composite by influencing the elastic–plastic transition temperature.

Girish et al. [35] studied the wear performance of magnesium hybrid composites reinforced with SiC and graphite, varying from 1, 2, and 3%. The improvement in wear rate was observed with increased SiC as well as graphite particles. This improvement was due to load bearing capacity of the hybrid composite. The increase in applied load results in the transition of oxidation wears to abrasion and delamination. SiC and graphite reinforcement in AZ91/SiC/Gr hybrid composite delayed this transition of oxidation to delamination wear.

Girish et al. [36] further optimized the tribological behavior of stir-casted AZ91/SiC/Gr hybrid magnesium composites using Taguchi experimental design. The wear test was done under dry conditions at normal load (20, 40, and 60 N), sliding speed (1.047, 1.57, and 2.09 m·s^{−1}), and composition (1, 2, 3 wt% each of SiC and Gr). Moreover; the effects of these parameters were also examined. The results revealed that the wear rate of the hybrid composite decreased with an increase in reinforcement composition while it increased with an increase in sliding speed and normal load. Normal load (34.17%) was the most significant factor for wear rate followed by speed (20.75%) and composition (11.70%). The lowest wear rate (0.0037 mm³·m^{−1}) was observed at 20 N load, 1.047 m·s^{−1} sliding speed, and 3% composition.

Trojanova et al. [37] investigated the mechanical and fractural properties of AZ91/SiC/Si hybrid composites synthesized using squeeze cast technology. The addition of SiC and Si in AZ91 results in an increase in tensile properties and thermal stability up to 200°C due to an increase of dislocation density and strong bonding between Mg₂Si/matrix. Although the strengthening effect of SiC and Mg₂Si diminished with an increase in temperature. From the impact test, it was shown that all composite was brittle at all temperatures. However, some improvement in ductility resulted at and above 200°C.

Svoboda et al. [23] compared the microstructural and creep behavior of unreinforced AZ91 and QE42 Mg alloys with their hybrid composites incorporated with SiC particles and short carbon fibers (SCF) using squeeze casting. It was observed that AZ91/SiC/SCF hybrid composites exhibited enhanced creep resistance than its monolithic AZ91 alloy due to the effective load-bearing capacity of reinforcement accompanied by redistribution of stresses in the magnesium matrix. However, hybridizing SiC and SCF with QE42 alloy was found ineffective in improving the creep resistance of hybrid composites. This was because

of weak adhesion between carbon fibers and reaction zone, debonding of SiC/matrix interface caused by creep cavitation and cracking of particles in QE42/SiC/SCF hybrid composites.

Yang et al. [38] successfully fabricated AS52/Alborex composite and AS52/Alborex/SiC hybrid composites by squeeze casting method without any void and defects. The microstructural and mechanical properties; i.e. microhardness and flexural strength were examined. The alborex and SiC were hybridized in AS42 alloy in 15 and 5 Vol%, respectively. A microstructural study using optical microscopy and SEM revealed that Alborex is uniformly distributed in the matrix while some clusters of SiC were observed. It was noticed that hybrid composite exhibited superior microhardness and flexural strength than monolithic alloy and alborex alone reinforced composite. This improvement in properties was seemed to be because of grain refinement, strengthening effect of hard SiC particles, and higher density of dislocation.

Zhou et al. [39] studied the tensile mechanical properties and strengthening mechanism of AZ91/CNT/SiC hybrid nanocomposites, fabricated by solid stirring-assisted ultrasonic cavitations. The hybrid reinforcement was added in 1 mass% of ratio 7:3. It was observed that the performance of hybrid composite increased with an increase in CNT content in hybrid reinforcement up to 7:3 ratio. Moreover, tensile properties and toughness of hybrid composite significantly increased with the addition of nanosize SiC and CNT. The strengthening mechanism for these improved properties was Orowan strengthening, grain refinement, and mismatch of CTE between matrix and reinforcement.

Thakur et al. [40] studied the mechanical and thermomechanical properties of Mg/nano-SiC composites and Mg/nanosized (SiC + Al₂O₃) hybrid composites, fabricated via powder metallurgy processing coupled with microwave sintering followed by hot extrusion. The results revealed that thermomechanical properties, i.e. CTE of Mg-based composites and hybrid composites, were more dimensionally stable than that of unreinforced Mg. However, mechanical properties, i.e. Y.S and UTS were significantly enhanced by reinforcing nano-SiC and hybrid (SiC + Al₂O₃) in Mg powder, while slightly reducing ductility. The hybrid composite with combined 0.5% nano-SiC and 0.5% Al₂O₃ exhibited the best combination of strength and ductility.

3 Aluminum oxide-reinforced hybrid magnesium composites

Mondal and Kumar [41] investigated the dry sliding wear properties of AE42 alloy-based hybrid composite

reinforced with saffil short fibers (SSF) and SiCp in longitudinal directions. The AE42/SSF composite and AE42/SSF/SiCp hybrid composites were fabricated by the squeeze casting technique. It was observed that the wear rate was decreased with the addition of SSF content in AZ42 alloy. Moreover; a further reduction in wear rate was noticed with reinforcement of SiCp in AE42/SSF composite. The improvement in wear resistance from hybridizing SiCp was due to its load-bearing capacity at higher loads, and it also delays the fracture of SSF at high loads. The microstructural investigation exhibited that abrasion was the dominant wear mechanism for AZ42 alloy-based composites. Mondal and Kumar [42] further conducted a study on the dry sliding wear behavior of AE42/SSF/SiCp hybrid composites in the transverse direction. It was found that hybrid composites reinforced with SSF and SiCp fabricated in a transverse direction also exhibited superior wear properties than composites reinforced with SSF alone. They also compared the wear resistance of hybrid composites, in transverse directions (experimental finding of this study) and longitudinal directions (experimental findings of previous study). And the important results illustrated in Figure 5 revealed that the wear rate of hybrid composite fabricated in transverse directions was lower than that of longitudinal directions.

In Figure 5, 1505 HC denotes 15% SSF and 5% SiC, 1010 HC denotes 10% SSF and 10% SiC, and 1015 HC denotes 10% SSF and 15% SiC. Meixner et al. [43] aimed of analyzing the phase-specific strains and stresses of AE42/SiC/Saffil alumina short fibers hybrid magnesium composites under compression load, fabricated using a direct squeeze casting process. Phase stresses and the load partitioning were calculated through measured average

internal elastic lattice strains under compression load evaluated using energy dispersive synchrotron X-ray diffraction analysis (EDX). The results revealed that elastic lattice strains possessed high plastic anisotropy. This plastic anisotropy can primarily be attributed due to the activation of different deformation modes in the form of crystallographic slip and mechanical twinning. Matrix plastic deformation affects the distribution of load among the participating phases. Within the analyzed stress interval from 0 to 400 MPa, three different loading regimes of hybrid composites were observed. The first region was characterized by overall linear elastic composite deformation, the second region was comprised of macro plastic composite deformation due to intensified matrix plasticity, and moreover, the twin volume fraction further increased in the third region.

Lu et al. [44] investigated the friction and wear performance of an Mg hybrid composite reinforced with nano- Al_2O_3 and CNTs. The tribological properties of the prepared hybrid composite were also compared with monolithic magnesium, Mg/ Al_2O_3 composite, and Mg/CNTs composites. The results obtained indicated that AZ31/ Al_2O_3 hybrid composite has enhanced hardness than monolithic AZ31 magnesium alloy. And at higher loads, tribological performance of the hybrid composite was improved by Al_2O_3 and CNT incorporation. Minimum wear rate and friction coefficient were achieved at AZ31/0.1 Al_2O_3 /0.2 CNT hybrid composite. The dominant wear mechanism at lower/normal loads was abrasion and delamination at higher loads.

Jo et al. [2] investigated the effect of SiC particle size (1,7,20 μm) on the tribological behavior of Mg/Saffil/SiC hybrid composites, fabricated by squeeze infiltration process. Ball-on-disk dry wear tests were performed at

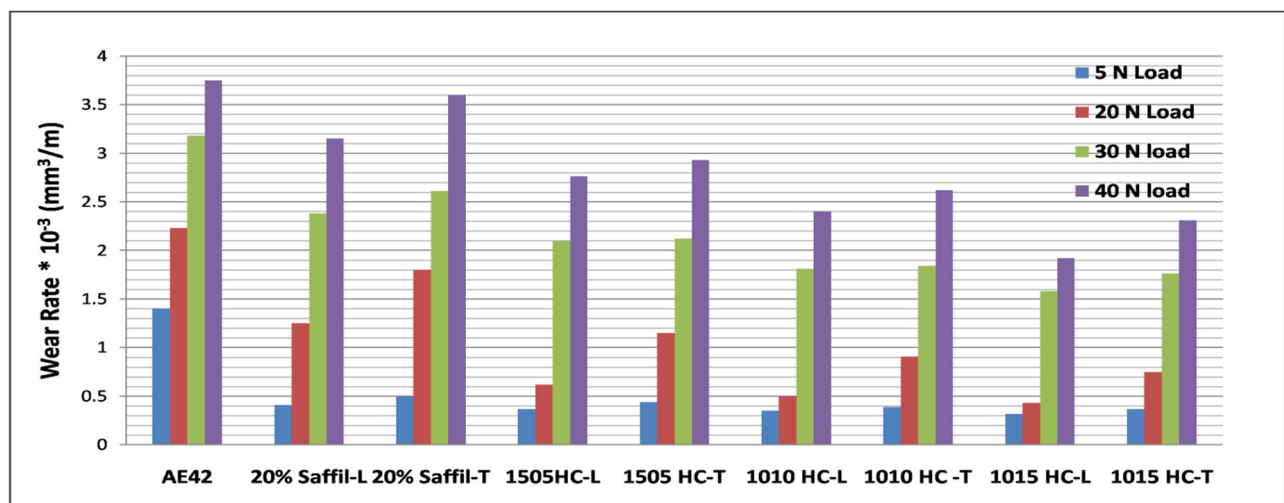


Figure 5: Comparison of wear rate for the AE42 alloy and its hybrid composites in Longitudinal direction (L) and Transverse direction (T) at different loading conditions (5, 20, 30, and 40 N), adapted from ref. [42].

different loads (5, 10, and 15 N) and sliding speeds (0.1 and $0.2 \text{ m}\cdot\text{s}^{-1}$), and their effect on wear rate was also experimentally examined. The results revealed that abrasion/adhesion was the wear mechanism at low speed and load, which was the further transition to severe abrasion at higher loads. The effect of the size of SiC was not significant under abrasion/adhesion or delamination wear mechanism; however, under severe abrasive conditions, the size of SiC largely influenced the wear rate.

Rashad et al. [17] reported the effect of heat treatment, presence of reinforcement, and their effect on tensile, compression, and microhardness of AZ31– $(1.5\text{Al}_2\text{O}_3\text{--}x\text{SiC})$ hybrid composite fabricated by powder metallurgy. The microhardness, 0.2% YS, and UTS was increased while fracture strain was decreased with an increase in reinforcement contents. The improvement in intensive properties seemed to be due to the uniform distribution of reinforcement and activation of non-basal slip systems. The AZ31/ Al_2O_3 /SiC hybrid composite after heat treatment showed a significant increase in tensile fracture strain.

Kumar et al. [45] developed magnesium hybrid composites reinforced with saffil short fibers and SiCp using the squeeze casting technique. The effect of reinforcement content on thermal cyclic behavior of AE42 alloy-based hybrid composite was examined in the temperature range of $30\text{--}350^\circ\text{C}$. The hybrid reinforcement (saffil short fibers and SiCp) reacts in a complex way and increases the reduction of CTE. The maximum reduction in experimental CTE ($15.4 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$) of the hybrid composite was reported at 10% saffil short fibers and 15% SiC particulate reinforcement.

Schroder and Kainer [46] in 1991 investigated that liquid infiltration can be successfully used for the production of magnesium hybrid composites with good property profiles. The MSR high-temperature alloy was reinforced with saffil (5 and 10 Vol%) and SiC (15 and 20 Vol%). The mechanical properties such as hardness, compressive strength, UTS, 0.2% proof stress, bending strength, and E-modulus of MSR/saffil/SiC hybrid composites were superior to those of unreinforced MSR Mg alloy. Excess chemical reactions between reinforcement and matrix could be avoided using a liquid infiltration process. One of the limitations identified was the high cost of performing production.

4 Titanium carbide-reinforced hybrid magnesium composites

Narayanasamy et al. [13] synthesized Mg/TiC and Mg/MoS₂ composites through a powder metallurgy route and further hybridized MoS₂ in Mg/TiC composites. The

influence of reinforcements, sliding speed, applied load, and sliding speed on the tribological properties of Mg/TiC/MoS₂ hybrid composites was also examined. Mg/TiC/MoS₂ hybrid composites revealed better hardness and wear resistance as compared to Mg/TiC and Mg/MoS₂ composites. The increase in hardness resulted in a stronger magnesium-reinforcement bond formed due to good wettability of TiC and MoS₂ with Mg, while better wear resistance was achieved due to the lubrication effect of smooth MoS₂-rich tribolayer. However, wear resistance decreases above 5% MoS₂ content due to clusters appearing at higher weight fractions of MoS₂. Sliding load and sliding distance are dominating factors affecting wear rate and coefficient of friction (COF). From the microstructural examination, it was revealed that abrasive wear and delamination were the major wear mechanisms of fabricated magnesium composites. Kumar and Narayanasamy [47] further fabricated Mg/TiC composites and Mg/MoS₂ composites and Mg/TiC/MoS₂ hybrid magnesium composites via powder metallurgy route. They investigated the effect of MoS₂ on the tribological properties of magnesium base composites and hybrid composites. Also, wear loss and friction coefficient was optimized by using Taguchi L27 orthogonal array. The individual reinforcement content, sliding load, speed, and distance were the parameters chosen for tribological behavior optimization. The results revealed that reinforcement content significantly affects the tribological behavior of the Mg hybrid composite. The addition of TiC and soft MoS₂ remarkably enhanced the wear resistance of hybrid composites. TiC content (39.02%) was the most significant factor for wear resistance followed by sliding distance (25.88%). However, MoS₂ content (47.48%) and TiC content (33.83%) significantly affected the friction coefficient of the hybrid composite.

Samkaranarayanan et al. [48] synthesized magnesium hybrid composites reinforced with 5.6 wt% of titanium particles and 2.5 wt% of nanosize alumina through disintegrated melt disposition technique followed by hot extrusion. The effect of ball milling of hybrid ($\text{Ti}_p + n\text{-Al}_2\text{O}_3$) reinforcement on microstructure and mechanical properties of hybrid composites was examined. The results indicated that impregnated hybrid reinforcement in magnesium matrix showed significant improvement in tensile strength, compression strength, and microhardness at the expense of ductility. However, when pre-synthesized ball-milled hybrid reinforcement was added to the magnesium matrix, mechanical properties were accompanied simultaneously by increase or retention of ductility.

Ma et al. [14] synthesized hybrid magnesium composites by reinforcing ($\text{TiB}_2\text{--TiC}$) particulates in AZ91 magnesium alloy via stir casting route. The in-situ ceramic reinforcement $\text{TiB}_2\text{--TiC}$ was fabricated through the master alloy technique

using a low-cost Al–Ti–B₄C material system. The advantage of using B₄C instead of pure boron was its lower cost at least 10 times of boron. The hybrid (TiB₂–TiC)p/AZ91 hybrid composite exhibits superior hardness and wear resistance than unreinforcement AZ91 alloy. These improvements in properties were due to the presence of TiB₂ and TiC particulates and Mg₁₇Al₁₂ eutectic phase.

Sahoo and Panigrahi [49] characterized hybrid magnesium composites reinforced with in-situ (TiC–TiB₂), fabricated via a novel hybrid fabrication technique, which was a combination of ball milling and stir casting. The AZ91 alloy ingots were drilled at different locations and filled with balled milled Ti and B₄C powders followed by vacuum stir casting. The mechanical properties, i.e. yield strength (YS), ductility, and tensile strength (TS) of as cast AZ91 alloy (ACB), as cast composite (ACC), homogenized AZ91 alloy (HACB), and homogenized as cast composite (HACC) were described and compared. The results obtained indicated that YS and TS of ACC were improved by 56 and 20%, respectively, than that of ACB, this elevation was contributed by uniform distribution of TiC and TiB₂ in-situ particles. The TS and ductility of HACB were enhanced by 29 and 100%, respectively, than that of ACB, while 26 and 100% respectively in HACC than that of ACC.

Paramosthy et al. [15] studied the effect of reinforcing TiC in AZ31/AZ91 hybrid alloy using DMD technique followed by hot extrusion. The intention of hybridizing AZ31/AZ91 alloy was to increase the nominal aluminum content of AZ31 by 3%. AZ31/AZ91/1.5 Vol% TiC hybrid composite showed superior tensile (YS and UTS) and compressive (only UTS) strength as compared to monolithic AZ31/AZ91 hybrid alloy. Moreover tensile and compressive failure strains of hybrid composite were also significantly enhanced due to the presence and uniform distribution of TiC nanoparticles.

Xiuqing et al. [50] studied the mechanical behavior of Mg–8(TiB₂–TiC) hybrid composite fabricated through remelting and dilution (RD) method. The results revealed that hybrid composite reinforced with (TiB₂–TiC) exhibited superior modulus, 0.2% YS, and UTS when compared to AZ91 alloy, while decreasing the ductility. The XRS analysis confirmed the presence of Mg, TiC, TiB₂, and Mg₁₇Al₁₂ phases in hybrid composites.

5 CNT-reinforced hybrid magnesium composites

Habibi et al. [51] simultaneously enhanced strength and ductility of pure magnesium by reinforcing Al/CNTs

particles. The hybrid composites were fabricated using powder metallurgy incorporated with microwave sintering followed by hot extrusion. While preparing composite CNTs weight percentage was fixed as 0.18 and aluminum weight percentages were varied at 0.5, 1 and 1.5. The results revealed that the value of elastic modulus, yield strength, UTS, and failure strain were improved by 3.6, 38, 36, and 42%, respectively, as compared to monolithic magnesium. The reason for enhanced strength can be ascribed to the grain refinement, crystallographic texture change, CTE mismatch hybrid reinforcement and matrix, and Orowan strengthening mechanism. However, failure strains for a hybrid composite decrease slightly by increasing Al content beyond 1 wt% because of an increase in the tendency of reinforcement clustering.

Cho et al. [27] conducted a study on the microstructural and thermal expansion behavior of hybrid CNT/SiCp/AZ91 magnesium composites processed and fabricated via squeeze infiltration. The hybrid performances were developed with 30 vol % of SiCp (9.3 m) and 5, 10, 15 Vol% of CNTs (20 m in length and 20 nm in dia.) by vacuum suction. The results showed that there was a considerable decrease in the coefficient of thermal expansion (CTE) with increasing CNT content in CNT/SiCp/AZ91 hybrid composites, which was due to CTE mismatch between reinforcement and matrix as CNTs possessed near-zero thermal expansion.

Wei et al. [52] examined the influence of sliding velocity on the tribological properties of monolithic Mg, Mg/SiC composites and Mg/SiC/MWCNTs hybrid composites, processed by powder metallurgy techniques. It was observed that hybridizing thermal stability and high modulus SiC and MWCNTs in Mg resulted in improved hardness. Moreover, improvement of wear resistance of hybrid composite was noticed under high load conditions, while no improvement at all was indicated at low loads. Hybrid composites showed different dominating mechanisms at different sliding velocities, i.e. abrasion and delamination at low sliding velocity and adhesion under higher velocity.

Sari et al. [53] fabricated CNT and cerium-reinforced hybrid magnesium composites using the powder metallurgy route. The effect of reinforcements and sliding speed on the tribological properties of hybrid composite was investigated via pin-on-disk test under dry and lubricating sliding conditions. The finding revealed that there can be different wear mechanisms for the same composite at different sliding speeds. Mg/MWCNT/Ce hybrid composite has improved friction coefficient and friction force between 100 and 200 rpm sliding speed.

Umeda et al. [54] characterized the friction and wear behavior of CNTs and Mg₂Si/Mgo compound-reinforced

magnesium hybrid composites fabricated via the powder metallurgy process. The results revealed that the addition of CNTs and $\text{Mg}_2\text{Si}/\text{Mgo}$ compound remarkably enhanced the tribological properties of hybrid composites. The reason can be ascribed to the strengthening by Mg_2Si dispersoids and self-lubricating effect of CNTs. The coefficient of friction of hybrid composites was low and stable under dry sliding conditions due to adhesion and stick-slip phenomena between sliding counterparts.

6 Boron carbide-reinforced hybrid magnesium composites

Aatthisugan et al. [11] examined the effect of B_4C and Graphite particle reinforcement on the mechanical and microstructural behavior of pure AZ91D magnesium alloy. The AZ91D/ B_4C /Gr hybrid composites were developed using the stir casting technique. The higher density was achieved by incorporating of B_4C in AZ91D which was further slightly increased with embedment of graphite particles. Moreover; low porosity value for AZ91D- B_4C -Gr hybrid composites was observed due to uniform stirring speed and also the size of reinforcements. The results also reveal that AZ91D- B_4C -Gr hybrid composite showed superior hardness and UTS than base AZ91D alloy, however; due to the addition of graphite, the hardness and UTS decrease for hybrid composite with respect to AZ91D- B_4C composites. Metallographic analysis shows uniform distribution of B_4C and graphite particles throughout the AZ91D matrix phase with a lack of cracks.

Samkaranarayanan et al. [25] further studied the microstructural and mechanical behavior of micro-Ti and nano- B_4C -reinforced hybrid magnesium composites. Mg-5.6Ti composite and Mg-(5.6Ti + x - B_4C) hybrid composite were also fabricated via disintegrated melt deposition technique. The evaluation of mechanical properties revealed that Mg-(5.6Ti + x - B_4C) hybrid composite exhibited improved strength properties simultaneously with an increase or retention of ductility. This enhancement in strength properties was the result of uniform distribution of hybrid reinforcement, good bonding between matrix and reinforcement, and grain refinement by localized dynamic recrystallization.

Li et al. [26] fabricated AZ91D-based hybrid composites by reinforcing $\text{Mg}_2\text{B}_2\text{O}_5\text{W}$ and B_4Cp particles via the squeeze casting technique. The mechanical and fractural investigations of fabricated hybrid composites were carried out. The results obtained revealed that reinforcement of $\text{Mg}_2\text{B}_2\text{O}_5\text{W}$ and B_4C remarkably improved the flexural

properties of hybrid composite by 29% as compared to monolithic composite, and B_4C was a major contributor to this enhancement. This elevation may be contributed to higher dislocation density in the matrix caused by CTE and elastic modulus difference between reinforcement and matrix. The microstructure and fracture study revealed random and isotropic distribution of reinforcement, moreover strong interfacial bond between matrix and reinforcement.

7 Copper-reinforced hybrid magnesium composites

Hasson et al. [55] investigated the effect of increasing copper content on high-temperature tensile properties of Mg/yttria/Cu hybrid composite fabricated by blend-press-microwave sintering powder metallurgy route. Magnesium powder of 60–300 μm , average size of yttria of 30–50 μm , and copper of 25 nm was used for the development of a hybrid composite. Increasing copperization up to 0.3 Vol% resulted in the most effective hybrid nano-reinforcement (Y_2O_3 + Cu) to reduce grain size from 20 to 8 μm and further caused improvement in 0.2%Y.S, UTS, and work of fracture. However, beyond 0.3%, tensile properties decreased due to the formation of agglomeration. The strengthening effect of hybrid reinforcement remained higher till up to 100°C; however, this effect diminishes gradually with an increase in test temperature (i.e. 200°C).

Hasson et al. [56] further studied the wear mechanisms for Mg/ Y_2O_3 /Cu hybrid nanocomposite synthesized through powder metallurgy technique coupled with blending press-microwave sintering. The pin-on-disk wear test was carried out against a hardened tool steel disk with a sliding speed of 1 $\text{m}\cdot\text{s}^{-1}$, a sliding distance of 1,000 m, and a load range of 5–30 N. The microstructural investigation of worm surfaces of hybrid nanocomposites revealed four wear mechanisms, i.e. abrasion, delaminating, adhesion, and thermal softening and melting at different test conditions. At a load of 5 N, abrasion was the only wear mechanism for hybrid nanocomposite; however, delamination came into play when the load was increased to 10 N. Mg/ Y_2O_3 /Cu hybrid composites exhibited no adhesion wear mechanism till below the load of 30 N; it was just activated at 30 N load.

Tun et al. [57] studied the tensile and compressive properties of Mg/ Al_2O_3 /Cu nanohybrid composites, which were fabricated via powder metallurgy processing coupled with microwave-assisted rapid sintering followed by hot extrusion. Incorporating nanohybrid reinforcement (Cu varied from 0.1 to 0.9 Vol% and Al_2O_3 fixed at 1 Vol%) in

magnesium results in a reduction in grain size, further enhancing yield and ultimate strength under tensile and compressive loading. The microstructural study revealed that there was a relatively uniform distribution of second phases in the Mg matrix. Moreover increasing Cu content up to 0.6 Vol% in hybrid composite results in an increase of second phase clusters instead of large size clusters; further increasing Cu content to 0.9 increases the size of clusters.

Seetharaman et al. [58] incorporated micro-titanium (Ti) and nano-copper (Cu) in pure magnesium using a disintegrated melt deposition technique and studied their effect on mechanical and microstructural properties of Mg. The micro-Ti and nano-Cu have limited/negligible solubility in pure magnesium and were added with and without preprocessing by ball milling. The results revealed that the addition of Ti and Cu results in grain refinement while simultaneously enhancing mechanical properties, i.e. microhardness, tensile, and compressive strengths. The Mg/Ti/Cu hybrid composites with ball-milled reinforcement exhibited superior tensile, compressive, and ductility as compared to those without ball-milled hybrid composites. This can primarily be attributed due to the formation of Ti_3Cu intermetallic phase, change in particle morphology, and good interfacial bonding achieved with ball milling of hybrid reinforcement. The enhancement in mechanical properties of Mg/Ti/Cu hybrid composites was also reported by Sankaranarayanan et al. [3] when hybrid composites were fabricated via powder metallurgy route coupled with rapid microwave sintering followed by hot extrusion. The effect of reinforcing individual micro-Ti, individual nano-Cu, and their combination in pure magnesium was investigated. It was observed that the addition of Ti, nano-Cu, and both resulted in improvement in tensile strength and hardness of pure magnesium while sacrificing the ductility. This was attributed to the higher volume content of metallic particles, lack of bonding between Ti and Mg matrix, and formation and agglomeration of Mg_2Cu intermetallic phases. However, the addition of ball-milled hybrid (micro-Ti + nano-Cu) reinforcement in pure magnesium exhibited best strength properties while retaining or improving ductility. This was due to modification in the morphology of Ti particles and the formation of Ti_3Cu phase resulting from ball milling of reinforcement.

8 Conclusions, scope, and future recommendations

Several aspects must be prevailed in order to strengthen the engineering applications of hybrid magnesium composites

such as fabrication techniques, influence of different reinforcements and their combinations, effect of hybrid reinforcements on the mechanical and tribological behavior, and its corresponding applications. The key experimental-based conclusions obtained from the prior works carried out are briefly as follows:

1. Tribological behavior of hybrid magnesium composites was improved by reinforcing self lubricating solid lubricants such as graphite, CNT, and MoS_2 as secondary reinforcements.
2. Wear rate of AE42/SiC/SSF hybrid magnesium composites in transverse direction was higher than that in longitudinal direction.
3. The literature reported in this article illustrated SiC (30%) as the most reinforced ceramic particles for fabrication of hybrid magnesium composites followed by Al_2O_3 (20%).
4. The literature review in this article demonstrated that powder metallurgy (36%) has been reported as the most contributing fabrication technique followed by squeeze casting (23%) for hybrid magnesium composites.
5. SiC particle-reinforced magnesium composites have higher wear and creep resistance than that of Al_2O_3 -reinforced magnesium composites.
6. The improvement effect on mechanical and thermo-mechanical properties of Mg/SiC/CNT hybrid composite by SiC was greater than that of CNT reinforcement.
7. Yttria and copper hybrid nano-reinforcement simultaneously increased strength and ductility of Mg/ Y_2O_3 /Cu hybrid composites when fabricated through powder metallurgy route coupled with blend-press-microwave sintering.
8. The in-situ ceramic reinforcement TiB_2 -TiC was fabricated via master alloy technique while adding Al-Ti- B_4C . The uniform distribution of reinforcement with negligible porosity was observed when the hybrid composite was fabricated at 900°C for 2 h.
9. Tensile strength and ductility of post homogenized AZ91/TiC- TiB_2 hybrid composites were enhanced by 26 and 100%, respectively, than those of unhomogenized hybrid composite.
10. The reinforcement of boron carbide (B_4C) leads to improvement of the interfacial bonding strength, flexural strength, hardness, and wear resistance of hybrid magnesium composites. B_4C remarkably improved the flexural properties of AZ91D/ $\text{Mg}_2\text{B}_2\text{O}_5$ w/ B_4Cp hybrid composite by 29% than that of monolithic composite.
11. SiC and short carbon fibers (SCF) hybrid reinforcement improved the creep resistance of AZ91 magnesium alloy while this hybrid reinforcement did not

showed any beneficial effect on creep behavior of QE42 magnesium alloy.

From the extensive literature review, it was investigated that magnesium hybrid composites reinforced with hard ceramics such as SiC, TiC, B_4C , TiC–TiB₂, and Al₂O₃ exhibited enhanced wear resistance, creep resistance, mechanical, and thermomechanical properties. However, the studies on mechanical properties such as impact strength, creep strength, flexural, and compressive strength have been less reported for ceramic-reinforced magnesium and its hybrid composites. Moreover, the tribological behavior of magnesium hybrid composites was improved by adding solid lubricants such as graphite, MoS₂, CNT, and graphene as secondary reinforcements. On the other hand, the effect of other solid lubricants such as MoS₂, WoS₂, and MWCNTs on the dry and under lubrication behavior of magnesium-based MMCs has not been less explored.

New biodegradable materials such as nano-hydroxyapatite (HAP), CNTs, calcium polyphosphate, and hybrid HAP + β -TCP particles have huge potential as reinforcements for magnesium-based MMCs for biomedical applications. Therefore, this area has tremendous scope due to similarity in the density of magnesium and human bone as well as good biocompatibility of magnesium and its alloys.

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