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Development and influence of tribomechanical properties on magnesium based hybrid metal matrix composites-a review

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Abstract

Composite materials are being widely studied for the last few decades, and it has optimized the day to day applications in the engineering field. In this advancement, the use and development of metal matrices was a significant outcome that concentrated on the addition of many particulate materials in a metal matrix at nano and micro levels. Among these Magnesium, metal matrices are having a high potential, especially in transport, defense, and aircraft industries. Many research works are being carried out to use the capabilities of Magnesium and has provided excellent results. This paper is an overview of the development, processing, and improvement of properties in Magnesium alloys. Various manufacturing processes such as self-propagating high-temperature method, stir casting, laser cladding, and powder metallurgy has been used to develop the magnesium composites for increasing the properties by using various wt% of reinforcements added in the matrix. The improvement in mechanical properties such as tensile strength, yield strength, hardness and tribological properties such as wear rate is reviewed. The different properties and capabilities of Magnesium alloys such as AZ31, AZ91, and ZE41 is also discussed from the various research works.

1. Introduction

In this new era of developing material science, engineering, and related technologies, composite materials have a proven platform of contribution to engineering research. The conventional materials have been replaced in many places due to their drawbacks, and many improvements have been incorporated to increase the desired properties [1, 2]. Among these hybrid metal, matrices are currently getting more attention due to their excellent mechanical, tribological, and physical properties in various applications. A hybrid metal matrix is a composite material that is being developed by adding two or more materials in the metal base. Many studies have proved that the hybrid metal matrices have improved strength, low cost, and weight and hence can be widely applied in aerospace and automobile applications.

Among these metal matrices, magnesium and its magnesium-based alloys are now possessing higher demands in aerospace, automobile, space, and other structural applications. D Panda *et al* in their work, has reported that magnesium alloys are having Hexagonal Close Packed structure and hence have less formability and limited-slip systems due to the structure [3]. Magnesium alloys are having 35% and 65% less density when compared to Aluminium alloys and Titanium alloys, respectively [4]. The density of Magnesium is found to be 1.74-2 gm cm^{-3} and is similar to bone density, and hence it is used in biomedical applications [5, 6]. The melting temperature of magnesium is low at around 654 °C [6]. Apart from these Magnesium alloys are having lower maintenance and production costs [7]. However, the Magnesium alloys have relatively low young's modulus, but this can be mitigated by using stiffer and harder ceramic particles as reinforcements [8]. The Magnesium hybrid metal matrix composites are produced by using various methods such as stir casting, powder metallurgy,

Table 1. Elemental composition of an ZE41 Mg alloy.

Element by wt%	Ce	Fe & Si combined	Mn	Zn	Zr	TR	Mg
ZE41 Mg alloy	0.56	0.008	0.01	3.5–5	0.56	0.8-1.7	Remaining

squeeze casting and friction stir processing. Magnesium is having a variety of popular alloys. The ZE41 has high-temperature friction and wear properties. This opens a broad scope of research on ZE41 magnesium alloy.

2. ZE41 magnesium alloy

There are different types of magnesium alloys in the world of material science, and all those have their significances in the versatile applications in engineering. There are two types of magnesium alloys, namely cast alloys and wrought alloys [9]. Among these ZE41 magnesium alloy, which is having zinc and rare earth elements, have gained significant applications in structural, aerospace, and biomedical applications [10]. In very recent research work by Zhicheng Li *et al* it is found that implantation of Nitrogen (N^+) has reduced the corrosion rate of AZ31 magnesium alloy and thus can be used in many clinical applications [11]. The composition of ZE41 Magnesium alloy is shown in table 1 given below. In the details of table 1, TR is the total weight percentage of the rare earth elements in the alloy. The presence of rare earth elements should increase the corrosion resistance, high-temperature creep, and tensile strength. When zinc is added to magnesium, corrosion resistance is increased, and it reduces the effects of corrosion formed by Iron and Nickel. K Kusnierczyk *et al* has reported that addition of ceramic in magnesium alloys can reduce corrosion and enhance mechanical properties [12]. Y Chen *et al* has found that due to the homogeneous microstructure without defects Bulk Metallic Glasses (BMG) based on magnesium has emerged as a new biodegradable material [13]. B Fang *et al* has found that the addition of carbon nanotubes in the magnesium matrix can increase the interfacial bonding between the matrix and reinforcement, which in turn helps in enhancing the mechanical properties [14].

3. Methods adopted for production of metal matrix

There are various methods used for the preparation of hybrid metal matrices of magnesium alloy. Each method has it is own advantages in certain specific applications, out of which the most commonly used ones are discussed below. So one must select the most suitable manufacturing process for manufacturing the magnesium metal matrix. The cost-effectiveness point of view for the production of matrices in different applications can also be evaluated.

3.1. Self propagating high-temperature method

Self Propagating High-Temperature method is a manufacturing process of alloys in which melting of reagents and products is done at first, followed by spreading of melt. Diffusion and convection of melted metal and non-metal takes place after this and it will create the nucleation of reliable products and crystal growth takes place.

D Mehra *et al* in their work, has reinforced a magnesium RZ5 alloy with Titanium carbide (TiC) by the Self-propagating high-temperature method [15]. RZ5 Magnesium alloy was heated at about 750 °C with argon shielding in a graphite container. Titanium mesh is heated at about 1650 °C in another coke-fired furnace in another graphite crucible. Then preheated graphite powder is added into the molten titanium at about 1850 °C at a holding time of 30 min with argon shielding. Then this molten titanium carbide is poured into the RZ5 alloy, which is molten and is stirred mechanically for 5 min Stirring helps to mix the *in situ* formed TiC particles uniformly. Then the cast metal is taken after proper solidification from a mild steel mold. It has to be noted that no intermetallic compounds will be formed since Mg does not react with titanium and carbide. The microstructural images has revealed that the grain size of the MMC has decreased when reinforced with TiC. So this will considerably increase the hardness value of the matrix since hardness and grain size are inversely proportional. The process involved in this method is shown in the schematic diagram shown in figure 1.

3.2. Friction stir processing (FSP)

FSP is mainly used as a surface modification property in manufacturing the metal matrices.FSP uses the principle of modification of structure by plastic deformation using a non-consumable tool that is advanced into the workpiece [16]. In FSP, a rotating tool is advanced over the workpiece surface. The plastic deformation of the surface takes place due to the heat generated by the friction between the surface of the workpiece and the shoulder of the tool and also due to the friction between the tool pin and workpiece. V V Kondaiah *et al* has

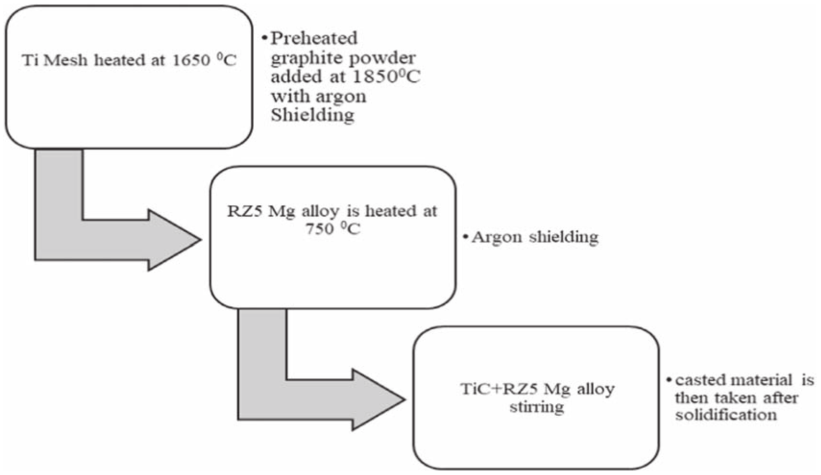

Figure 1. Self propagating high-temperature method.

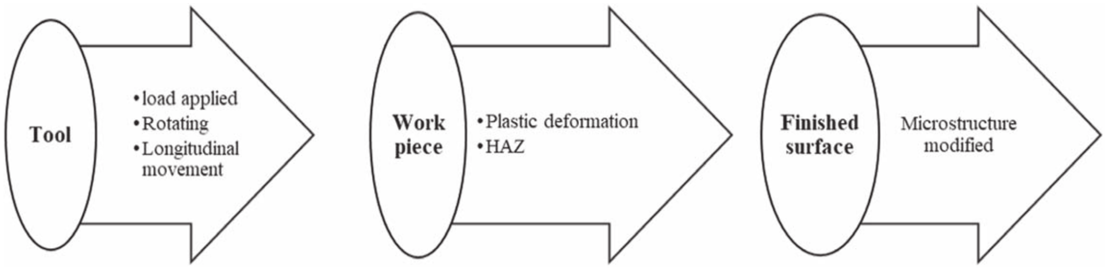

Figure 2. Friction stir processing.

commented that the heat thus generated will serve the purpose of stirring, and thus the microstructure is modified [17].

In a research work by A Srinivasanaik *et al* ZE41 magnesium alloy plates were processed with the FSP technique by a tapered high-speed steel tool having shoulder diameter 16 mm [18]. FSP was conducted on the specimen at different rotational speeds of the tool at 450, 650, 850, 1050, 1250 rpm. The tool is longitudinally transversed at a speed of 50 mm min^{-1}. The depth of the tool is kept constant. The results showed that the FSP on cast Mg alloy at 650 rpm showed finer grain size and hardness values. When the rotational speed is increased, it is inferred that the grain size is decreased. It is to be noted that the tensile strength has increased from 210 to 272 MPa, and the yield strength has increased from 150 MPa to 184 MPa.

C Vasu *et al* has utilized FSP to create a Calcium reinforced ZE41 Mg alloy [19]. H13 tool steel is utilized in this work with shoulder diameter 15 mm and the pin tapers from 5 mm to 2 mm diameter. The tapering length is 3 mm. On the workpiece, a groove of 1mm width is first created, and it is having a depth of 2 mm. Then the groove is filled with Ca, and the pinless FSP tool is advanced over the surface for proper filling of Ca powder. Then the FSP process is done with 1400 rpm tool speed and a transverse speed of 25 mm min^{-1}, and thus the composite is manufactured.

In another study, it is observed that FSP was a powerful tool for breaking the clusters of SiC particles. It refines the particle size and distributes the particles uniformly in the Mg matrix [2]. In this work, the tool used for FSP was an H13 cylindrical threaded pin having 1 mm pitch, 5 mm diameter, 4.7 mm depth, and shoulder diameter 16 mm. The schematic diagram of friction stir processing is shown in figure 2.

3.3. Stir casting

In stir casting, the base metal is heated at elevated temperature in an inert atmosphere to avoid oxidation process. A Manivannan and R Sasikumar made use of a vortex stir casting setup having a furnace, reinforcement feeder, a mechanical stirrer, and a pouring set up at the bottom to transfer the molten slurry to mold [20]. In a research work by T Thirugnanasambhandham *et al* the base metal with 65% Mg and 35% Al is heated at 750 °C in an inert environment and then reduced the temperature to 550 °C, thereby obtaining a semisolid state. At this point, 50 nm alumina particle is added at 100 rpm and is mixed uniformly, which is also done in an inert atmosphere.

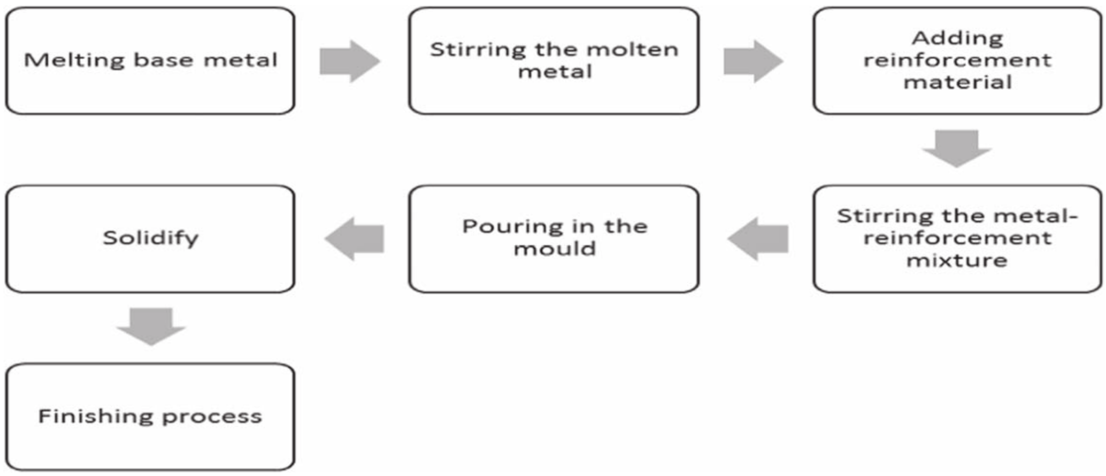

Figure 3. Processes involved in the stir casting process.

After this step, the molten metal is cast, and then proper machining is done for the desired shape and dimension [21]. It was observed that the composite with 10% weight of alumina is showing better wear resistance. N Bala *et al* has found that to avoid melting of magnesium after preheating, SF_6 along with Argon gases, is added during the stir casting process [22].

Hybrid metal matrices were formed through the stir casting route by adding 1% and 2% weight TiO_2 and 0.5% weight graphene on an AZ91 Mg alloy [23]. It has seen that the wear rate has reduced significantly for the hybrid metal matrix at all load conditions due to the reason that graphene works as a solid lubricant. From the optical microscopic examination, it is clear that the crests and troughs in the parent AZ91 matrix were more. S Kumar *et al* has reported that the major disadvantage of stir casting is the fixing of melting temperature of reinforcement material, which is noted as three times that of base metal [24]. It is reported that the agglomeration of reinforcement particles in the molten material is a highly decisive factor in the surface finish and crack formation [25]. The schematic diagram of the stir casting process is represented in figure 3. The scanning electron microscope (SEM) image of AZ91 Mg alloy added with 1 and 2 wt% of TiO_2 and 0.5 wt% graphene showed that the cracks and voids are very less in metal matrix composite.

3.4. Laser cladding

Laser cladding is an interdisciplinary technique that unites laser technology, control system, and Computer-Aided Manufacturing (CAM).It is a highly efficient surface modification technique used for providing bonding between coatings and the base substrate [4]. In this technique, a laser heat source is used to deposit a thin layer of materials on a moving substrate, the movement of which is controlled by the operating system. In another work by F Liu *et al* hybrid Laser cladding and Friction stir processed Al–Cu coating on AZ31 magnesium has shown strong interfacial bonding providing more corrosion resistance [26]. A simple schematic diagram for the laser cladding process is shown in figure 4. In another research work, AZ61 Mg alloy is coated with nano TiO_2 and Al_2O_3 reinforcements in 5, 10, and 15 weight percentages through laser cladding technique [27]. It is inferred that solubility of titanium is less in Magnesium, but it has a chance to react with silicon and form as $TiSi_2$. Further, It is quoted that Silicon has a high affinity towards Magnesium, and hence silicon shows a tendency to bond in Mg-rich zones [28]. Wear tests were carried out on the specimen with and without reinforcements by using a pin on disc tribometer. It is observed that increasing the reinforcements has decreased the wear rate and increased the hardness value. It is noted that the wear rate has decreased from 935 microns to 235 microns. The coefficient of friction and frictional force is more for Al_2O_3 alloys.

3.5. Powder metallurgy

Powder metallurgy is the process in which the metal or alloy powders are mixed properly and then compacted in a high-pressure dye followed by sintering at high temperature for proper bonding of particles.A composite metal matrix with AZ31 as the base metal matrix having 5% alumina and SiC varying from 0 to 8% is prepared by using powder metallurgy technique in a work done by E Karthick *et al* [29]. The particles are mixed uniformly, and 200 MPa is applied for compaction for 30 s. Then sintering is done at 450 °C and is done at the temperature rate of 10 °C min^{-1} for 20 min and allowed to cool. In a research work, Mg alloy (Mg-3Zn-0.7Zr-1Cu) was taken as the matrix material, and hybrid metal matrix was prepared by blending the matrix with micro and nano alumina reinforcements. It is then followed by pressing in a dye and punch setup, followed by the sintering process. After

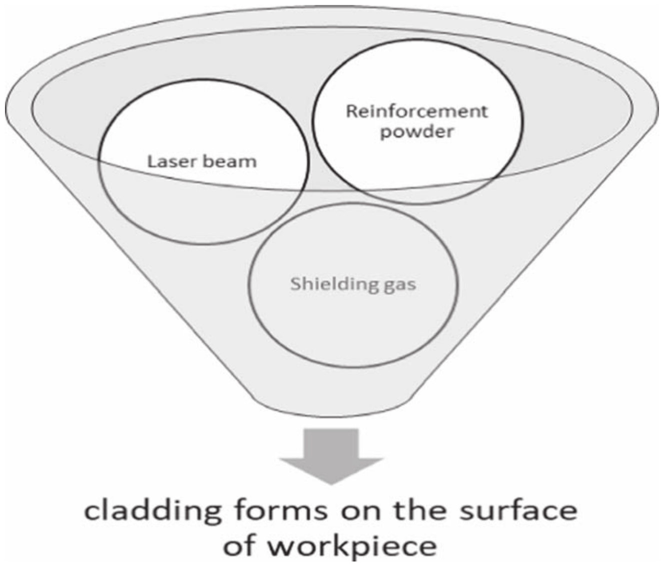

Figure 4. Laser cladding process.

Figure 5. Processes involved in powder metallurgy process.

this, hot extrusion is carried out at 400-degree Celcius [30]. In a work done by M Rashad *et al* Mg–3Al–1Zn matrix of 70 μm particle size is reinforced with Al_2O_3, and SiC particles, which was manufactured by the powder metallurgy process was prepared, followed by a hot extrusion process [31]. N Selvakumar *et al* has proved that Mg matrix when reinforced with 10 wt% of TiC and 7.5 wt% MoS_2 (Molybdenum disulfide) has reduced the wear because of the proper dispersion and interfacial bonding of reinforcement particles [32]. In their work by S Tamang *et al* the Mg alloy was mixed mechanically with Yttria(Y_2O_3) for about 40–50 min, which is then pressed hydraulically by applying 80–130 kN using a hydraulic press for 15–20 s for better compaction [33]. The process involved in the powder metallurgy process is shown in figure 5.

After reviewing different works carried out in this area several manufacturing aspects can be pointed out such as the powder metallurgy process is the most cost-effective process for manufacturing the matrix by maintaining a controlled level of porosity.The stir casting process is also economical in mass production but achieving a uniform distribution of particles in the matrix is difficult since fine selection of stirrer, stirring speed, and stirring time has to be done.

4. Tribo-mechanical properties considered for evaluating the performance of metal matrix

There are various properties of hybrid metal matrices which should be considered for its applications.The most important properties are mechanical and tribological properties especially when it is used in aerospace and automobile applications.The important mechanical and tribological properties which are discussed in this paper are hardness, tensile strength, yield strength, grain size and wear rate.

4.1. Hardness

Hardness of a material is the resistance against abrasion or indentation and is normally measured by using Brinnel, Vickers or Rockwell hardness testing machines.In a research work by D Mehra *et al* magnesium alloy RZ5 was reinforced with Titanium carbide(TiC) having 10 wt% contribution [15]. The outcome of this research showed that the hardness of RZ-5 reinforced with 10% TiC has increased considerably compared to the RZ-5 alloy without reinforcement which was prepared by self-propagating high-temperature method. The hardness value has increased for the 15% weight TiO_2 and Al_2O_3 coated AZ61 Mg alloy when manufactured by laser

Table 2. Hardness comparison of Mg Matrix with reinforcement.

Reference no.	Base matrix	Reinforcement	Method	Hardness	
				Matrix	Reinforced
[15]	RZ5 Mg	TiC−10% wt	Self-propagating high-temperature (SHS)	73 VHN	105 VHN
[27]	AZ61 Mg	TiO_2–15% wt	Laser cladding	55.9BHN	72.4BHN
[27]	AZ61 Mg	Al_2O_3–15% wt	Laser cladding	55.9BHN	68.3BHN
[23]	AZ91 Mg	TiO_2–2% wt, Gr-0.5% wt	Stir casting	65.8VHN	72.2VHN
[19]	ZE41 Mg	Ca	Friction stir processing	60.98 ± 5.3 HV	73.7 ± 9.9 HV
[2]	Mg–99.9% pure	SiC-9% wt	Friction stir processing	34 ± 5 VHN	106 ± 3VHN
[29]	AZ31 Mg	SiC-8% wt Al_2O_3–5 wt%	Powder metallurgy	64.53VHN	75.16VHN
[7]	Mg	SiC and Al_2O_3–10 wt%	Powder metallurgy	36.3VHN	45.3VHN
[22]	Mg	B_4C-9 wt%	Stir casting	42HR	78HR

cladding process due to the refinement of grain size [27]. S Jayabharathy and P Mathiazhagan has observed that the Vickers Hardness number (VHN) of AZ91 Mg alloy produced by stir casting route has elevated when reinforced with 2% weight of TiO_2 and 0.5% graphene since graphene acts as a solid lubricant for uniform mixing of reinforcement particles [23]. It is quoted that the microhardness value of composite has increased from 60.98 ± 5.3 Hv to 73.7 ± 9.9 Hv when it is reinforced with calcium by the FSP method [19]. It was seen that the Vickers hardness value of the composite has increased to 106 when reinforced with SiC from 34 of the pure cast Magnesium at a tool speed of 1300 rpm [2]. This increase in hardness is attributed to the reduced grain size of the composite. The SiC hard particles prevent dislocation movements, which has caused an increase in the capacity of load-bearing for the composite. The hardness of the AZ31 metal matrix, when mixed with SiC and alumina, has increased from 64.53 Vickers hardness to 75.16 hardness value, which is mainly due to the presence of SiC particles which bears the load [29]. The hardness value of AZ91 alloy, when reinforced with 2% weight of Al_2O_3, has increased to about 25%. The Vickers hardness number of pure Mg has increased from 36.3 to 45.39 for a metal matrix reinforced with 10% SiC and Al_2O_3 particles, which was prepared by the powder metallurgy process [7]. The hardness is showed to have increased by 31% when AZ91D magnesium alloy is added with ZrO_2 due to the dispersion and plastic deformation of the particles [34]. The mechanism of hardening occurs in the matrix due to the reinforcement particles entering the lattice structure of soft, ductile materials. R Jojith *et al* has enumerated that this entry of particles blocks the motion of atoms where there is a dislocation and thus providing higher resistance to plastic deformation [35]. The comparison of hardness values of different magnesium-based matrices are shown in table 2. The hardness value of the metal matrices is highly contributed by the uniform dispersion of reinforcements and the microstructural examination reveals that finer grain size results in harder material.In a work by A Asgiri *et al* waste magnesium chips of AZ91 after machining is collected and reinforced with 2.5% and 5% SiC particles through stir casting and found that the microhardness has increased by 28% and 46.6% respectively [36]. In a research work by Yu Yan Han *et al* it was found that the average grain size of as-cast MZC0.5Mn alloy having 0.5 wt% manganese has reduced by 40.1% when compared to the MZC(Magnesium-Zinc-calcium) as-cast alloys [37]. This will increase the hardness of alloy when mixed with manganese.

4.2. Tensile strength

The tensile strength of a material is the maximum amount of tensile stress a material can withstand before failure, which can be experimentally found out by using a universal testing machine. The tensile strength of TiC reinforced RZ5 Mg alloy has increased from 179 to 195 MPa [15]. This is because the TiC will act as load bearers in the composite. The tensile strength of the matrix when reinforced 2% weight of TiO_2 and 0.5% graphene has increased to 149.1 N/mm^2 from 84.3 $N\ mm^{-2}$ [23]. The ultimate tensile strength has increased to 141 MPa for a composite having a 9 weight % of Si from 117 MPa [2]. It may be due to the fine and uniform distribution of SiC particles. The tensile strength is found to be more for nano alumina mixed Mg alloy when compared to the matrix prepared by micro alumina particles [30]. The increase in SiC content along with Al_2O_3 has increased the tensile strength of an Mg–3Al–1Zn alloy by 0.2% [38]. The metal matrix composite has a network structure, and hence it does not show a brittle nature [39]. However, it shows elastic-plastic nature, which is the failure mode observed in these matrices [39]. The Young's modulus of composite according to mixing rule is found [39] by equation (1), where E_C is the young's modulus of the composite. E_R and E_M are young's modulus of reinforcement and matrix respectively.V_M and V_R are volume fractions of matrix and reinforcement.

Table 3. Tensile strength comparison of Mg Matrix with reinforcement.

Reference no.	Base matrix	Reinforcement	Method	Tensile strength(MPa)	
				Matrix	Reinforced
[15]	RZ5 Mg	TiC −10% wt	Self-propagating high-temperature (SHS)	179	195
[23]	AZ91 Mg	TiO_2–2% wt, Gr-0.5% wt	Stir casting	84.3	149.1
[2]	Mg-99.9% pure	SiC-9% wt	Friction stir processing	90	68
[22]	Mg	B_4C-9wt%	Stir casting	65	135

$$E_C = E_M V_M + E_R V_R \tag{1}$$

In another research work, it inferred that the addition of nanoplatelets of graphene in magnesium had increased Young's modulus, Ultimate tensile strength, and yield strength [40]. The comparison of tensile strength of magnesium metal matrices, when added with different reinforcements, are shown in table 3.

4.3. Yield strength

The yield strength of a material is a critical design parameter which represents the initiation of plastic deformation which can be plotted from the stress-strain diagram of a material. The yield strength of the RZ5 Mg matrix reinforced with TiC at 10 weight% has reduced from 140 to 121 MPa [15]. The presence of microcavities and particle cracking has increased the yield strength of the SiC reinforced composite to 90 MPa from 68MPa [2]. Yield strength of AZ91 composite when mixed with nano Al_2O_3 is found to have elevated due to the grain refinement and Orowan strengthening due to the presence of nanoparticles in the range of 50 nm [41]. The metal matrix of Mg–3Al–1Zn when reinforced with Al_2O_3– SiC has increased by 0.2%, which is due to the loss of strain at fracture when the SiC content is increased [38]. The yield strength of Magnesium based matrix composite has increased from 0 to 85 MPa when added with B_4C particles at 9 wt% in a work done by N Bala [22]. K K Alaneme *et al* found that the yield strength has increased by 0.2% when the Magnesium matrix is added with nickel particulates. However, the ductility is found to have decreased [42].

4.4. Grain size

The grain size of a material is the average diameter of the reinforcement particles in the matrix which can be characterized by microstructure evaluation through scanning electron microscopy and x-ray diffraction spectroscopy. Grain Size of the RZ5 Mg matrix reinforced with TiC at 10 weight% has decreased from 250 to 20 μm, and hence the hardness of the matrix was increased [15]. The grain size of the ZE41 Mg alloy is found to have decreased from 110 μm to 7 μm when reinforced with calcium, and hence the hardness of the composite material is found to have increased [19]. When compared with pure Mg, the grain size has reduced significantly when added with SiC particles, and the reduced grain size of 3.1 μm was obtained from 705 μm at an optimum FSP sample obtained by rotating the tool at 1300 rpm. L Rogal *et al* observes has observed that the MgO (Magnesium oxide) in size range 30 nm–50 nm where formed by the thixomolding process due to the addition of a semisolid slurry. The addition of slurry provides homogeneous mixing in the composite matrix resulting in the enhancement of properties [43]. The strength of the composite is inversely proportional to the grain size according to the Hall Petch formula [41].

$\sigma_y = \sigma_0 + k_y/\sqrt{d}$, where σ_y = yield stress

σ_0 = material constant for the starting stress of dislocation movement.

k_y = strengthening coefficient

d = average grain diameter.

4.5. Wear rate

The wear of material is the volume of material removed from the surface per unit sliding distance. It is the most critical tribological parameter to be studied whenever new metal matrix composites are developed for the applications in sliding. T F Su *et al* has reported that the main mechanisms of wear are abrasion, oxidation, delamination, thermal softening, adhesion, and surface melting [44]. The wear rate is found by using equation (2) [45].

$$\text{Wear rate} = \text{Volume of material removed } (mm^3)/\text{Sliding distance (m)} \tag{2}$$

The effect of load and sliding distance is being studied extensively in many kinds of literature. The wear rate of the metal matrix composite has reduced than the base matrix. However, it is found by B M Girish *et al* that when a load is increased, the wear rate also is increased [45], and there exists a transition load at which the wear rate of both the unreinforced and reinforced composite starts suddenly increasing. S Shanker *et al* observes it., that if the sliding speed for the pin on disc experiment increases, the temperature between the contact surface of pin and matrix reaches the vicinity of melting point of the matrix, leading to solidification of pin around the periphery increasing wear rate [46]. It is found that the composite coatings with Tungsten carbide(WC)-17Co on AZ80 Magnesium alloy is having higher microhardness and resistance of wear when compared to alloys of Magnesium substrate which were produced by cold spraying method [47].

The different mechanical and tribological properties of hybrid magnesium metal matrices are studied and it has to be noted that the weight percentage of reinforcements and grain size along with the transition load plays a vital role in defining the properties of matrix.

5. Design of experiments (DOE)

It is a tool that helps to obtain specific information on the parameters regarding the outcome of experiments, which directly affects the response variables. The conventional method of multifactorial method of design can be replaced by using the Taguchi method, which employs the use of Orthogonal arrays [48].

5.1. Taguchi method

Taguchi method is an approach based on the orthogonal array and is having the capacity of giving less variance for the parameters which control the experiments when it is set at optimum condition [49]. B A M Pasha *et al* has stated that it is a method where the expenses are meager and are being used nowadays by the researchers to formulate a relationship between the impact of parameters and it is interactions in experiments [48]. This technique has reduced the number of iterations by enhancing the parameters in the experiment trials [50]. In this work done by Satnam Singh *et al* the selected the normal load, track diameter and sliding distance as the parameters which are varied at 3 levels [50]. It is written by D Mehra *et al* that they have used an L27 orthogonal array, which means there are 27 experiments that are represented in the 27 rows followed by three levels at 13 columns [49]. M A Almomani has noted that the effect of test parameters and percentage weights of the reinforcing materials against the wear rate is being analyzed by using Taguchi's L16 orthogonal array at the levels of normal load and sliding speed [51]. The Signal to Noise(S/N) ratios are then found from the arrays, and it is analyzed under various conditions viz. 'smaller is better nominal is better' and 'larger is better' [52]. For example, in the development of new metal matrices, the wear rate factor has to be selected as 'smaller the better' [52].

5.2. Grey relational analysis (GRA)

GRA is the analysis in which multiple process parameters are optimized to obtain multiple response variables which the research addresses. R Arunachalam *et al* has stated that it is combined with the Taguchi Method to obtain the results since the Taguchi approach has the disadvantage of optimizing only one response variable, which is governed by different parameters [53]. GRA is utilized to convert multiple process variables to single Grey Relational Grade(GRG).GRG is calculated by assuming that the weights are equal for all response variables [53]. Here also, S/N ratios are found and based on the application, the maximizing or minimizing condition shall be achieved. S Prabhu *et al* has noted that the most influential parameter is obtained by finding the difference between the maximum and minimum average GRG [54]. The GRG can be found by using equation (3).

$$\mathrm{GRG} = 1/\mathrm{n}^{*}\sum \mathrm{Grey\ coefficient} \tag{3}$$

Finally, the confirmation test is done by using the parameters of the experiments, which are getting Rank 1.

6. Conclusion

The development and influence of Magnesium based metal matrices have been reviewed extensively. The methods of development, like stir casting and powder metallurgy, were most commonly used in a majority of works. It is evident that the addition of particles in the micro and nanolevel, especially ceramics, has enhanced the wear and mechanical characteristics of all the metal matrices developed. However, it has to be noted that the research works conducted on ZE41 Magnesium alloy are very less when compared to other alloys of magnesium. So the development of Hybrid metal matrices, which utilizes ZE41 Magnesium as a base matrix in specific applications, can open the doors of research in the composite material field.

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