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An overview of the future prospects and challenges of TiC-reinforced magnesium matrix composites

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Abstract

Magnesium matrix composites (MMCs) reinforced with Titanium Carbide (TiC) has significant attention in the field of advanced materials due to their enhanced mechanical properties and lightweight characteristics. This Metal matrix composites (MMCs) are of great interest in industrial applications for its lighter weight with high specific strength, stiffness and heat resistance. The processing of MMCs by casting process is an effective way of manufacturing. This review paper provides a comprehensive analysis of recent advancements in the development, characterization, and applications of Mg-TiC composites. It also included synthesis methods, liquid metallurgy and powder metallurgy techniques, and the impact of TiC reinforcement on the microstructure and properties of the magnesium matrix. This review paper discusses the improvements in hardness, strength, and wears resistance achieved through TiC reinforcement, as well as the influence of reinforcement volume fraction and particle size on composite performance. Additionally, it highlights the challenges associated with the processing and fabrication of Mg-TiC composites, such as issues related to interfacial reactions and the dispersion of TiC particles. The performance of composites depends upon the right combination and composition of reinforcement material with the matrix material. The present study, based on the literature review, reinforcing material, processing route, Taguchi and GRA methods, mechanical and tribological properties of Mg based metal matrix composites containing single and multiple reinforcement. This paper presents few of the available literature review the combination of reinforcement material with magnesium matrix metal. Magnesium metal matrix composites with reinforcement(s) and filler materials are finding increased applications because of improved mechanical and tribological properties. Addition of reinforcing materials such as Al_2O3, SiC, B_4C, metallic glass, etc., is one of the ways to enhance various mechanical and tribological properties of Mg based MMCs. Waste materials may used as reinforcement such as fly ash, rice husk ash, etc. for low cost reinforcement which may results in better mechanical and wear properties. The current applications in aerospace, automotive, and structural engineering are examined, underscoring the potential benefits of Mg-TiC composites in high-performance environments. An essential goal of this review is arouse the interest of academicians, scientists/technologists and industrialists in the use of those materials for the fabrication of MMCs. This hybrid composite can replace the conventional material used in automotive applications involving tribological importance. Future directions for research are proposed, emphasizing the need for optimized processing techniques and further exploration of the mechanical behavior and long-term performance of these composites. This reviews aims to provide a detailed understanding of the state-of-the-art in Mg-TiC composites and guide future innovations in this promising material system.

Keywords: MMCs; Titanium Carbide; Mg-TiC Composites; Mechanical Properties; Wear Resistance

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

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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].

Shru et al (2006) has studied different tribological applications, aluminum alloys are desirable because of their low densities, but they are not used because of their extremely poor wear resistance. Therefore the development of aluminum matrix composites is receiving considerable emphasis in meeting the requirements of various industries. In previous work, it was shown that the incorporation of both hard ceramic particles (e.g. alumina [1–3], silicon carbide [4–6], silica [7] or zircon [8,9]) and a soft solid lubricant (e.g. graphite [10–12] or mica [13]) into an aluminum alloy increased the wear resistance. The density of Magnesium is found to be1.74-2 gm cm−3and 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, 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. Literature Review

2.1. 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 Zhi cheng 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 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].The literature review has illustrated the following indispensable information on the fabrication aspects and their properties evaluation of Mg based composites.

Gnanavel babu et al. [34] has investigated the corrosion behaviour of magnesium (Mg-AZ91D) alloy reinforced with nano metal oxides (ZnO, MnO, and TiO_2) using the tribo-corrosion methodology. The mechanical characteristics of the materials were investigated using ASTM standards for AZ91D alloy, AZ91D/ZnO, AZ91D/MnO, and AZ91D/TiO_2 composites. The AZ91D/TiO_2 nano composite has higher hardness (122.71 HV) and tensile strength due to decreased porosity and smaller grain size (200.7 MPa)

Jojith et al. [35] investigated the fabrication of LM13/TiO2 (12 wt%)/MoS2 (3 wt%) hybrid metal matrix composite and unreinforced alloy using liquid metallurgy route and evaluation of mechanical properties and adhesive wear characteristics. Micro structural investigation revealed homogeneous distribution of reinforcements in matrix. Hardness and tensile properties revealed that the composite had attained an improvement of 16.5 and 35%, respectively, over alloy. Wear characteristics were analyzed using pin-on disk tribometer by varying load (10–40 N), sliding velocity (1–4 m/s), and sliding distance (500–2000 m). Results revealed that, with increasing load and sliding velocity, an increment in wear rate was observed for both alloy and composite, while a decline was observed with increasing sliding distance for composite and vice versa for alloy

Asgari et. al. [36] showed concern with the reuse of AZ91 magnesium-alloy chips to fabricate Mg-based composites. The fabrication process requires to collect and clean magnesium chips and then mix them with SiC particles as reinforcements. Finally, this composition was melted and stirred by a stir casting method to fabricate the AZ91/SiC composites. The results clearly showed that not only magnesium chips waste can be reused in a sustainable way, but also that they improve the reinforcement distribution substantially, leading to enhanced mechanical properties so that the composite yield strength increases by 62.7% when adding 5% SiC particles, volume percentage.

Yan Hun et al. [37] explored the changes of microstructure, mechanical properties and corrosion resistance of ternary Mg-3Zn-0.2Ca (wt.%) with different contents of Mn (0.3, 0.5, 0.7, 0.9, wt.%) are studied. With the increase of Mn content, the grain size of as-cast alloy first decreases and then increases, this indicated that the amount of Mn affects the degree of sub cooling of the alloy. At the 320°C/24 h homogenizing treatment, the large and uneven dendrites are transformed into uniform equi-axed grains, the mechanical properties of alloys with different Mn contents were different on the basis of Mg-3Zn-0.2Ca (wt.%) alloy. The electrochemical results showed that the corrosion potential of Mn-contained alloys are increased compared to ternary Mg-3Zn-0.2Ca (wt.%) alloy, and 0.5 wt.% Mn-contained alloy performs the best result.

Jayalakshmi et. al. [38] has investigated that highest volume fraction(25%) resulted in a hardness value (165BHN) that is nearly twice that of the unreinforced base alloy (85BHN). Tensile tests were conducted at four different test temperatures, viz. 25 (room temperature), 100, 150 and 200°C, respectively. The ultimate tensile strength of the unreinforced base alloy was very sensitive to temperature and undergoes a drastic reduction in strength as the test temperature increases. At the highest test temperature the strength drops to almost one-third of its room temperature value. The % elongation of the alloy increased initially with increasing test temperature.

Lim et al. [39] has reported that elastic modulus, macro-hardness, and density of Mg-Al/Si-C shows higher than Mg-Al. The volumetric wear rates for the Mg–9Al alloy and its Si Cp-reinforced composite showed that wear rates were greater at the higher load of 30 N. At the lower load of 10 N, the addition of Si-Cp reinforcement brings slight but consistent improvement to the wear resistance of the Mg-Al alloy (about15–30%), except at the highest speed of 5m/s, where the wear rates are nearly equal.

Jiang et al. [40] has observed that the hardness of B_4C/Mg composites with (20 vol. %) B_4C particulate was higher than that of as-cast magnesium ingot. The volumetric wear rate of B4C/Mg composite was obviously less than that of as-cast magnesium ingot as expected.

Poddar et al. [41]has investigated mechanical properties of SiC (15vol.%) reinforced cast magnesium matrix composites (AZ91D) and reported that the increase in hardness and elastic modulus compared to Mg-15 vol.% of SiC monolithic composite containing 15 μm size SiC particles is significantly higher than the composite with 150 μm size particles. The ultimate tensile strength and ductility of composite materials was reduced compared to unreinforced alloy.

Tang et al. [42] has studied mechanical properties of magnesium matrix composites reinforced with10wt.%W14Al86 alloy particles and reported that the UTS increased from 360 to 458MPa with increasing the milling time from 0.5 to 2h, and then decreased to278MPa as for 4h. The hardness continuously increased with increasing the milling time.

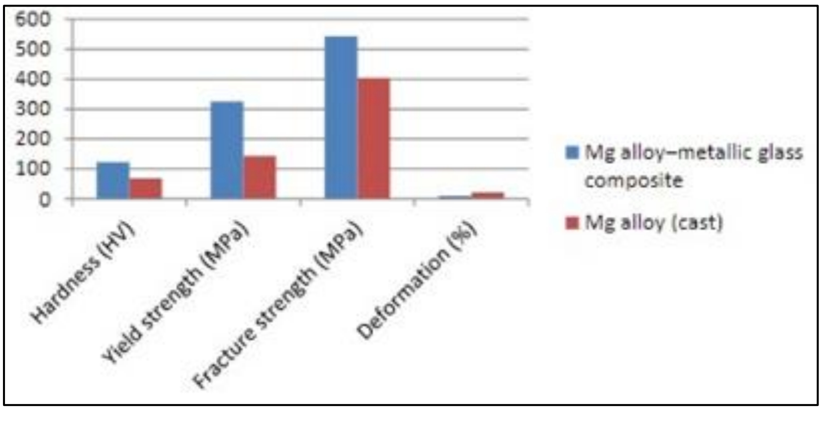

Figure 1 Comparison of Mechanical Properties of Mg-Metallic glass composite and Mg Alloy (Cast)

Dudina et al. [43] had studied magnesium alloy (AZ91) matrix composite reinforced with metallic glass. It was concluded that hardness, yield strength, fracture strength of Mg alloy–metallic glass composite is higher than Mg alloy (cast). The % deformation of Mg alloy–metallic glass composite was less than Mg alloy. The Comparison of hardness, yield strength, fracture strength, and % deformation of Mg alloy-metallic glass composites and Mg alloy (cast) is shown in Fig. 1.

Hong et al. [44] has studied thixotropic compression deformation behaviour of SiCp/AZ61 magnesium matrix composites. The flow stress of SiCp/AZ61 composites increased with the increase of volume fractions of SiC particles. The flow stress of semi-solid SiCp/AZ61 composites is sensitive to temperature and strain rate. The lower the temperature and the larger the strain rate, the higher the flow stress.

Güleryüz et al. [45] has reported Brinell hardness values of the samples seen that the highest hardness value was obtained with 9wt.% B_4C reinforced Mg composite. Flexural strength value of the samples show that Mg-B_4C(3% by weight) gives highest flexural resistance value.

Li et al. [46] had prepared magnesium matrix composites reinforced with $Mg_2B_2O_5$ and B_4Cp and reported the additions of $Mg_2B_2O_5$ and B_4Cp can remarkably enhance the flexural properties of the composites.

Muley et al. [47] investigated that the addition of Si particles grain size decreased by as much as 30% to 45% in 3 and 5 wt %Si/AZ91 composites. Both the hardness and the ultimate compressive strength increased by almost 90% upon addition of 5%

Si. Wang et al. [48] reported that the UTS increased as the micro-SiCp increase from 0% to15% due to grain refinement, but UTS decreased when the particle contents increased from15% to 20% due to particle aggregations. SEM images of the composites with different volume fraction shows that Particle distribution was uniform in the composites except the distribution of 5vol% composite. In addition, there were some micro-aggregations in the 20% composites.

Bhingole et al. [49] had studied the mechanical properties of $MgO–Al_2O_3–MgAl_2O_4$ dispersed magnesium alloy composites. It is reported that the AZ91-6.5-UST composite specimens exhibited best mechanical properties with its hardness, yield strength and strain hardening exponents higher by 64%, 43%, and 115%, respectively, as compared to the AZ91 alloy. As the amount of reinforcement increased, the MMCs became more wear resistant.

Selvam et al. [50] the dry sliding wear behaviour of zinc oxide (0.5vol.%) reinforced magnesium matrix nano-composites reported that wear rate was found to increase with the load and sliding velocity. However, the coefficient of friction decreased as the sliding distance increased.

Rashad et al. [51] had reported the addition of Al-GNPs particles into pure magnesium has significantly improved the hardness values. From tensile test it is observed that, a 131% enhancement in Young's modulus, a 49.5% enhancement in yield strength and a 74.2% increment in fracture strain.

Nie et al. [52] reported that increase in the number of multidirectional forging (MDF) passes leads to decrease of the un-recrystallized regions in the microstructure and the increase of degree of dynamic recrystallization (DRX). The influence of multi directional forging on microstructures and mechanical properties of a SiCp/AZ91 nano composite shows that after1 MDF pass, yield strength and ultimate tensile strength of the nano composites were significantly enhanced while the elongation to fracture is decreased**.**

Viney et al. [53] had studied the comparison of mechanical properties and effect of sliding velocity on wear properties of AL6061-4%Mg-Flyash(10%,15%and20%), AL6061-4%Mg-4% Graphite-Flyash(10%,15% and20%) hybrid metal matrix composite by stir casting.

In the present study, magnesium (Mg) is used as the matrix material because it is lightest in nature and having very good vibration and damping characteristics. Because it is not sufficiently strong in its purest form, it is alloyed with various elements in order to gain certain specific properties, particularly high strength-to-weight ratio. Magnesium is also an alloying element in various nonferrous metals. Magnesium alloys are also used in structural and non-structural application where light weight is primary importance. Magnesium MMCs have great use potential in the structural components in the aerospace and automobile industries mainly because of their low density and high specific strength.

3. Different Methodology 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

It 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 Mehraet 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 inter metallic compounds will be formed since Mg does not react with titanium and carbide. The micro structural 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.

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 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 transverse at a speed of 50 mm/min.. 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 to272 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., 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.

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 Sasi kumar 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 Thirugnana sambhandham 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, 50nm alumina particle is added at 100 rpm and is mixed uniformly, which is also done in an inert atmosphere. 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, SF6 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 scanning electron microscope(SEM)image of AZ91 Mg alloy added with 1 and 2 wt% of TiO2and 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 TiSi2. 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 Al2O3 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 200MPa is applied for compaction for 30s. Then sintering is done at 450°C and is done at the temperature rate of 10°C/min. 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 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 70μm particle size is reinforced with Al2O3,and SiC particles, which was manufactured by the powder metallurgy process was prepared, followed by a hot extrusion process[31]. N Selva kumar 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. 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.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. Performance and evaluation of Metal Matrix by using tribological mechanical properties

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-5alloy without reinforcement which was prepared by self-propagating high-temperature method. The hardness value has increased for the 15% weight TiO2 and Al2O3 coated AZ61Mgalloy when manufactured by laser cladding process due to the refinement of grain size [27].

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 RZ5Mgalloy 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 TiO2 and 0.5% grapheme has increased to 149.1N/mm2 from 84.3 Nmm−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 anMg–3Al–1Zn alloy by 0.2% [38].

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 RZ5Mgmatrix reinforced with TiC at 10 weight% has reduced from 140 to 121 MPa [15]. The presence of micro cavities 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 Al2O3 is found to have elevated due to the grain refinement and strengthening due to the presence of nano particles in the range of 50 nm[41]. The metal matrix ofMg–3Al–1Zn when reinforced with Al2O3– 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 RZ5Mgmatrix reinforced with TiC at 10 weight% has decreased from 250 to20 μm, and hence the hardness of the matrix was increased [15]. The grain size of the ZE41Mg alloy is found to have decreased from 110 μmto7 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 thixo-molding process due to the addition of a semi solid slurry. The addition of slurry provides homogeneous mixing in the composite matrix resulting in the enhancement of properties [43].

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. 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 [45-53] 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 multi factorial method of design can be replaced by using the Taguchi method, which employs the use of orthogonal arrays [54].

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 [55]. B 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 [54]. This technique has reduced the number of iterations by enhancing the parameters in the experiment trials [56]. 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 [56]. 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 13columns [55]. MA Almomani has noted that the effect of test parameters and percentage weights of therein forcing materials against the wear rate is being analyzed by using Taguchi's L16 orthogonal array at the levels of normal load and sliding speed [57]. 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' [58]. For example, in the development of new metal matrices, the wear rate factor has to be selected as 'smaller the better' [58].

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 [59].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[59]. 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 [60].

6. Challenges and Solutions

6.1. Particle-Matrix Interaction

The wettability of TiC with the magnesium matrix is a major challenge. Solutions such as surface coatings or alloying elements to improve wetting and bonding are under investigation

6.2. Processing Difficulties

The high reactivity of magnesium with TiC and the difficulty in achieving a homogeneous particle distribution can affect the quality of the composites. Advanced processing techniques and optimized parameters are being developed to address these issues

7. Applications

7.1. Aerospace and Automotive Industries

Mg-TiC composites are increasingly used in aerospace and automotive applications where high strength-to-weight ratios and wear resistance are critical. Their use in engine components, structural parts, and high-performance alloys is expanding.

7.2. Structural and Wear-Resistant Components

The enhanced mechanical properties of Mg-TiC composites make them suitable for structural applications and components subject to high wear conditions, such as gears and bearings.

8. Summary and scope for future studies

Future research should focus on:

- **Optimizing Processing Techniques**: Developing new methods to enhance the dispersion of TiC particles and improve the bonding between particles and the matrix.

- **Exploring New Reinforcements**: Investigating alternative or additional reinforcements to further enhance the properties of magnesium matrix composites.
- **Long-Term Performance Studies**: Evaluating the long-term performance and reliability of Mg-TiC composites in various operational environments.

In the present critical review, an attempt has been made to provide an insight and information that might be proven useful for future investigations on the development of metal-matrix composites using industrial and agricultural waste materials. On account of their attractiveness such as unique structure/morphology, chemical composition, unlimited availability and low cost, industrial and agricultural waste materials constitute viable alternatives to replace matrices and/or reinforcing phases in metal-matrix composites. Their performance depends strongly not only on their origin, chemical composition and morphology, but also on the choice of processing route (chemical or mechanical). It was found that with the exception of fly ash, up to date, no industrial-scale endeavor has been undertaken to use waste materials in metal-matrix composites. Consequently, plenty of opportunities can be envisioned. For example, the use of cenosphere flyash, Celceram (Cellular ceramic Materials, a specific fraction of power plant coal fly ash) could be a window of opportunity in this field. Metal-cenosphere fly ash was introduced to the industry by the Center for Composite Materials and Center for Advanced Materials Manufacture, University of Wisconsin-Milwaukee for the fabrication of Crumple zones, frame members, frame reinforcements, pedestrian impact zones, batteries (Lead-fly ash composite), intake manifolds, accessory brackets, low load brackets, oil pans, valve covers, alternator covers, water pumps, etc. Because of the unique properties of cenosphere fly ash, addressed in a comprehensive manner in section 2, Celceram seems to have potential as are inforcing constituent for fabrication of MMCs. However, in terms of high volume utilization quite likely, a series of economic barriers will have to be faced and overcome. For instance, diminishing the content of some deleterious constituents through chemical modification in fly ash will result in an enhancement of the final physical and mechanical properties of the composites. Most of the ceramic industrial waste materials contain valuable oxides such asAl_2O_3, SiO_2, MgO, Fe_2O_3, etc., which can act as a reinforcing phases in their original composition or by a modification by means of suitable composites processing routes. Furthermore, in terms of chemical composition, reutilization of metallic industrial wastes requires lower production costs. And although agricultural waste materials cannot be used in their original form in MMCs, choosing the most efficient procedure can yield ceramic phases with unique and valuable structure. As a rich source of silica, rice-husk ash has been used in several investigations, but depending on fabrication route (powder metallurgy, stir casting, etc.)its unique and valuable structure can be negatively altered, or even worse, be destroyed. Therefore, besides the benefits of its chemical composition, setting a different and appropriate route can help keep its original morphology. From this critical review it is apparent that due to an underestimation or lack of information of the real potential of industrial and agricultural wastes, their application in the development and fabrication of metal-matrix composites has been neglected. Although this endeavor perhaps might not compete in volume terms, the generation of high added value products is by itself a significant achievement. In addition, an environmentally friendly approach will be cultivated by not having to produce synthetic phases.

9. Conclusion

Magnesium matrix composites reinforced with Titanium Carbide represent a significant advancement in material science, offering improved mechanical properties and wear resistance. While there are challenges associated with their synthesis and processing, ongoing research is addressing these issues and expanding their application potential. This review highlights the current state of knowledge and provides a foundation for future innovations in this promising material class.The results shows that the generated prediction model have a good potential to be used as a practical tool with its high reliable performance and practical significance for the prediction of density and hardness of AA2024-SiC nano-composites. The development and influence of Magnesium based metal matrices have been reviewed extensively. It can be concluded that the developed hybrid composite has better mechanical and tribological properties and can be applied for automotive tribological applications. 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 nano-level, 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. A number of processing routes are available for the synthesis of Mg based MMCs either on solid or liquid processing. These are squeeze casting, powder metallurgy, stir-casting, disintegrated melt deposition technique, two-step stir casting, ultrasonic processing, stir casting assisted by ultrasonic treatment processing, semisolid stirring assisted ultrasonic vibration and multidirectional forging, microwave assisted rapid sintering technique etc. Out of these processing route stir casting is the one of the simplest and low cost synthesis method of MMCs.

From the above literature survey, It is concluded that following points.

- The process parameters such as stirring speed, preheating temperature of reinforcement, time of stirring, stirring temperature, pouring temperature etc., plays an important role on improvement of distribution of reinforcement in magnesium based MMC in an stir casting process.
- Addition of reinforcing metallic materials such as Al_2O_3, SiC, B_4C, metallic glass, etc., is one of the way to enhance various mechanical and tribological properties of Mg based MMCs especially load bearing capacity.
- When graphite is added composites decrease in tensile and hardness was observed whereas with graphite addition specific wear rate decreases.
- The mechanical properties also depend upon the size of reinforcing material. If the size of reinforcing material increases the ultimate tensile strength and ductility of composite materials was reduced compared to unreinforced alloy.
- The improvement of mechanical as well as tribological properties with addition of organic materials such as fly ash; rise husk ash etc., in hybrid composites.
- Very limited work has been reported regarding addition of organic material to magnesium matrix composite. Hence addition of organic material to magnesium matrix composite should be further explored.

Compliance with ethical standards

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No conflict of interest to be disclosed.

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