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Advancement in Magnesium Metal Matrix Composites: A Mini-Review of Production Techniques, Properties, and Applications

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***Abstract*— The advancement of research in new engineering materials has led to the development of magnesium metal matrix composites (Mg MMCs). This study critically examined the production techniques, properties, and applications of Mg MCs. Powder metallurgy and casting routes were the two classifications of the techniques for producing Mg MMCs. The mechanical, tribological, corrosion, and bio-compatibility properties of the composites and the application of the Mg MMCs were reviewed. Orowan strengthening mechanism, Hall Petch strengthening mechanism, and Taylor strengthening mechanism were the mechanisms responsible for the improvement of the strength of the composite. The study further highlighted the areas for future studies.**

Keywords*— Magnesium alloy; metal matrix composites; powder metallurgy; casting; materials engineering

I. Introduction

The development of new materials that are light in weight and have uncompromising material strength is required in this new age of technology and manufacturing. The improvement of the mechanical and metallurgical properties of a specified material is one of the interests of an engineer in the manufacturing sector [1–4]. New material development, especially in the area of metal matrix composites (MMCs), has increased significantly over the years [5,6]. This was due to the special properties of the newly developed materials in finding applications in specified areas [7–9]. Some of the light metal alloys that have served as matrix metals are aluminium, magnesium, titanium, copper, and so on [5,10–12]. However, the most utilized metal alloys are aluminium and magnesium as reflected by many studies [4,13,14].

In the production of metal matrix composites, reinforcement materials wither particles, fibers, or whiskers are introduced to the matrix to give it new desired properties. The reinforcements commonly employed are SiC, B_4C, TiB_2, Al_2O_3, TiC, and so on [14–18]. The reinforcements utilized have a high melting point with minimal solubility in the base metal [13]. Recently, there has been advancement in the area of reinforcement usage. Prior, single reinforcement materials were employed in the production of MMC. However, hybrid reinforcements are being employed for the synthesis of MMCs. The hybrid reinforcements consist of at least two reinforcing particles that form intermetallic to strengthen and improve the properties of the base alloy [19–22]. With the advent of metal matrix composites with hybrid reinforcements inclusion, complex microstructures have been obtained compared to monolithic reinforced matrices. More so, there have been more complications in analyzing and describing the influence of specific reinforcing phases on the mechanical and tribological properties [13,23,24]. In all, some properties are enhanced by one reinforcement while the other reinforcement can lower another important property. Hence, it is germane to state that the development and comprehensive characterization and analyses of hybrid reinforced MMCs are very important for the proper description of their behaviours.

This study aims to review past studies on magnesium MMCs in line with the major production techniques, mechanical properties, and wear properties. The various areas of application of Mg MMCs are also highlighted.

II. MAGNESIUM METAL MATRIX COMPOSITES

Magnesium MMCs are composites produced with reinforced ceramic materials either monolithic or hybrid reinforcements. These materials are developed to achieve a variety of applications in the automotive and aerospace sectors for the reduction in fuel consumption, and biomedical applications [25,26]. Magnesium and its alloys are used as matrix alloys because they are the lightest of all the matrix metals that are popularly used [4,27]. However, the disadvantages of magnesium alloys are their low modulus and poor creep resistance at high temperatures. Hence to overcome these delimitations, the introduction of the required reinforcements at the right quantity in the matrix is germane. This is the genesis of magnesium MMCs.

In the process of developing Mg MMCs, the matrix-reinforcement interface plays a role in the determination of the mechanical properties. More so, the bond strength between the matrix and reinforcement as a result of the chemical reaction can result in product formation at the interfaces. Consequentially, the interface assists in the transference of stress from the base alloy to the reinforcing particulates without the separation of the duo. However, poor and medium adhesion will produce different effects. These principles are similar to what is obtainable in aluminum metal matrix composites as reported by [2,28–30].

III. TECHNIQUES OF PROCESSING MAGNESIUM-BASED METAL MATRIX COMPOSITES

Numerous techniques have been employed in the development of Mg-based MMCs. However, these numerous techniques can be grouped into (i) powder metallurgy technique and (ii) casting technique [31]. Powder metallurgy (PM) is cost-effective and simply used in developing Mg MMCs. This technique ensures uniform dispersion of the particulate reinforcements in the base alloy under a relatively lower processing temperature than melting and casting. In the manufacturing of products via PM, pressure and temperature can be applied simultaneously through spark plasma sintering (SPS) or hot press sintering (HP). The basic steps involved in PM are shown in Fig. 1.

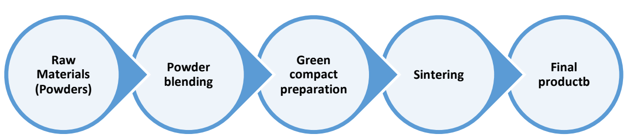

Fig. 1. Powder metallurgy process

In the casting technique, the matrix alloy is melted and continuously stirred for homogeneous distribution of the reinforcement when introduced into the molten alloy. Mechanical or inductive stirring is usually employed. A mold of the desired shape is made where the liquid melt is discharged after sufficiently stirring and allowed to solidify. After solidification, the cast product is removed for further finishing processes. This process is used because it is cheap and is a convenient method of production of Mg MMCs in large quantities. Some of the methods under this technique are stir casting, squeeze casting, high-pressure die casting, disintegrated melt decomposition, and so on [1,31]. Table 1 shows some studies with techniques for processing composites.

TABLE 1: Technique of processing of Mg MMCs

S/N	Composite	Processing technique used	Ref.
1.	Mg/5HAP/15TiO_2	Conventional sintering	[32]
2.	Mg/1 GNP	Semi powder metallurgy	[33]
3.	Mg/SIC	Conventional powder metallurgy	[34]
4.	Mg/GNPs	Multi-step dispersion route (Semi-solid stirring, high energy ultrasonic processing, and hot extrusion)	[35]
5.	Mg/CAN	Gravity die-casting	[25]
6.	AZ91/TiC/SiC	Stir casting	[13]

IV. REVIEW OF THE PROPERTIES OF MAGNESIUM METAL MATRIX COMPOSITE

To ascertain the functionality of a newly developed engineering material, the material must be subjected to a series of tests – mechanical, tribological, and corrosion. Therefore, this section considers investigating some reported properties of Mg MMCs produced using different reinforcement. Xiang et al. [35] obtained enhanced mechanical properties when magnesium MMCs were reinforced with graphene nanoplatelets (GNPs)via the multi-step dispersion technology. Although, the GNPs were well dispersed but in-homogenously distributed in the matrix. The GNPs increase significantly improves the mechanical properties of the MMCs. The strengthening mechanisms were reported to be from grain refinement and load transfer obtained by the two-dimensional and wrinkled surface of the GNPs reinforcement. The mechanical properties and microstructure of AZ91 MMCs reinforced with Ti and SiC particulates were developed and investigated by Braszczyńska-Malik [13]. The study utilized the hybrid reinforcement at 15 vol.% in the matrix alloy. It was revealed that there was an improvement in the mechanical properties of the reinforced AZ91 Mg matrix alloy compared to the un-reinforced matrix alloy.

The surface micrographs of the tensile surface of the reinforced AZ91 MMCs revealed dimples and river patterns. The utilization of Ti particles did not undergo cracking during the uniaxial tensile loading. More so, the below 4 µm particle size of the SiC used lowered the occurrence of crack propagation from the SiC particles in the MMCs. Hence, there is a strong connection between the Mg MMCs and the Ti particles. This is a confirmation of the coherent interface creation between these components.

Using the PM route, hybrid reinforced MMCs with SiC and Al_2O_3 at different ratios were developed and characterized [34]. It was revealed that there was an improvement in all the mechanical properties investigated compared to the unreinforced alloy. The peak of hybrid reinforcement for better performance of the properties was at 10% SiC and 10% Al_2O_3 particulates. The tribological properties also revealed that at 15% SiC and 15% Al_2O_3, more materials are lost due to weak bonds between the reinforcement and matrix. However, 10% SiC and 10% Al_2O_3 samples showed minimal material reduction compared to other sample designations.

A better matrix bonding is expected to be obtained with in-situ generation of micro and nanoparticles in Mg-melt. Hence, [25] developed hybrid Mg-based MMCs via in-situ reaction with the addition of ceric ammonium nitrate (CAN) to the matrix metal melt. There was the in-situ formation of intermetallic phases of CeO_2, MgO, and $CeMg_{12}$ in various sizes and types. The intermetallic phases of the particulate reinforcement improved the mechanical properties of the composites developed. The different strengthening mechanisms such as the Taylor strengthening mechanism, Orowan strengthening mechanism, and Hall-Petch strengthening mechanism, were responsible for the achieved improvements in the mechanical properties [25,36]. The internal morphology of the developed composites as well as the fractured surfaces were critically examined using a Scanning electron microscope (SEM). X-ray diffraction (XRD) and Energy dispersion spectroscopy (EDS) were used to explore the nature of the CAN particles as well as the intermetallic phases.

The powder metallurgy technique was employed in the synthesis of Mg MMCs with graphene nanoplatelets (GNPs) as reinforcement [37]. The high-energy ball milling procedure was used for the dispersion of the GNPs in the Mg powder. A series of characterizations on the developed composites were carried out including mechanical properties, corrosion behaviour, and cytotoxicity assessment. The study revealed the excellent utilization of GNPs as reinforcing particulates in Mg-based alloys. It found good applications in the development of biodegradable Mg-based composite implants. Through the synergetic strengthening mechanism, the mechanical properties of the Mg-based alloy improved with the GNPs inclusion. Through the cytotoxicity assessment, no significant toxicity was revealed with the Mg-GNPs composites. Hence, it concluded that novel biodegradable implant materials for load-bearing applications could be obtained provided the value of the GNPs incorporated into the MG alloy is below 0.3 wt.%. Furthermore, Dey and Pandey [38] in a review done for different reinforcements addition into Mg-matrix alloy concluded that Mg MMCs-SiC have higher wear and creep resistance, unlike the Mg MMCs-Al_2O_3. With the utilization of carbon nanotubes (CNTs) as reinforcement, the wettability and bonding strength of the Mg-CNTs composite are improved. More so, better-sliding wear resistance is obtainable in Mg MMCs than in its matrix alloy. The more the reinforcement in the composites, the more their resistance to wear. The introduction of fibers into Mg MMCs improves the tensile strength; however, there is reduction in ductility of the composite products.

In some recent review studies, the influence of nanoparticle (reinforcement) variations in Mg alloys was examined along with relevant processing techniques [39, 40]. Mg metal matrix composites were developed using AZ31-Mg MMCs reinforced with MoS_2, SiC, and ZrO_2 through the powder metallurgy route. The mechanical, metallurgical, and tribological properties were investigated. The micrographs of the developed composites showed uniform distribution of the reinforcement particulates. Ductile and brittle fractures occurrence were observed via SEM. The developed composites were proposed to find applications in different aerospace and automotive areas [41]. Carbon nanotubes were used as reinforcement in AZ31 alloy to produce AZ31 Mg-MMCs using the powder metallurgy route. The developed composites were characterized to determine the impact of sintering on the composites using differential scanning calorimetry (DSC). The study also assessed the corrosion behaviour of the composites in a salt environment (NaCl solution) [42].

V. APPLICATIONS OF MAGNESIUM MMCS

Developed Mg-based MMCs are majorly utilized in the automotive, aerospace, biomedical, and electronics applications. Many studies have been examined on their bio-compatibility in the body and toxicity to the body. The materials promised to be useful in all these areas.

VI. FUTURE ADVENTURE ON MAGNESIUM MMCS

Although there are consistent ongoing studies on Mg MMCs; however, the available studies on Mg MMCs are few compared to studies available on Al MMCs. More studies should be done in the area of introducing micro and nano-size particles as reinforcements of both ceramic and bio-waste derivatives either monolithically or hybrid into the matrix alloy. Furthermore, research should be tailored towards optimizing the different processing techniques and parameters for both the Mg alloys and Mg MMCs. Novel forming techniques to improve the formability and properties of the Mg MMCs should be invented.

VII. CONCLUSION

Magnesium alloy is among the most important metal alloys that are utilized in different sectors such as automobile, aerospace, biomedical, and electronics. The review study was conducted on Mg MMCs reinforced with ceramic particles. The methods of production were classified into two – Powder metallurgy and casting technology. The introduction of reinforcements improves the mechanical and tribological properties of the Mg MMCs. The strengthening mechanisms for the improvements of the mechanical properties were identified. The biomedical utilization of the biodegradable Mg MMCs was ascertained with the cytotoxicity test. The tribological properties of the Mg MMCs were noted to improve with increased reinforcement to a certain volume percentage. More so, new fabrication technologies should be invented, while processing parameters and techniques were suggested to be optimized.

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