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Review Article

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Magnesium and Solid Lubricants based Self-lubricating Metal Matrix Composites: A Comprehensive Review and Future Directions

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Abstract

The present study focuses on the current development in the area of magnesium (Mg) based self-lubricating metal matrix composites (MMCs). Mg alloys and its composites are gaining importance in the field of aerospace, automobile, and medical industries due to their properties like light in weight, strength to weight ratio, stiffness, castability, and machinability. This study has imparted lights on the dry sliding wear behaviour of various Mg-based composites and hybrid composites fabricated with addition of different solid lubricants reinforcement's particles such as Graphite (Gr), Boron Carbide (B_4C), Carbon Nanotubes (CNTs), Molybdenum Disulfide (MoS_2), Tungsten Disulfide (WS_2), Aluminium Oxide (Al_2O_3), and Graphene Nanoplatelets (GNPs). Apart from this, their physical and mechanical properties are also discussed. It was found that addition of solid lubricants in Mg and its alloys leads to improved tribological properties due to formation of lubricative protective layer between sliding counter parts.

Keywords

Solid lubricants, Graphite, Graphene, Titanium carbide, Self-lubricating composites, Magnesium matrix hybrid composites

Introduction

In the era of limited natural materials, important steps are being taken into consideration to improve the fuel efficiency and reduce the harmful gas emission. The extensive research is going on new lightweight materials which have light specific strength and can be used for weight reduction in automobile and aerospace industries [1]. Researchers find magnesium suitable to replace various commonly used materials by reason of its very low density (1.74 g/cm^3) when compared to other materials. It is found that its density is two thirds of Al (2.7 g/cm^3), one quarter of Zn (7.14g/cm^3) and one fifth of steel [2]. Mg also possesses some advantages as good machinability and structural properties but it's high corrosion rate and low wear resistance limits the use of Mg in various industries [3]. To overcome these constraints the researchers are adding hard ceramic particles such as Al_2O_3, SiC, WC, B_4C, WS_2, and Zirconium (Zr) to enhance the physical and mechanical properties, while solid lubricants like graphite, SiC, MoS_2, and WS_2 particles have been incorporated in Mg and its alloys to enhance its self-lubricative property [4-8]. There solid lubricants create a protective layer between the mating sliding counterparts and reduce the wear rate of components. Mg-based composites and hybrid composites have been fabricated using various fabrication methods such as stir casting, powder metallurgy, friction stir processing, infiltration, compo casting and squeeze casting. Khatkar et al. [9] showed the percentage contribution of different fabrication processes for Al and Mg-based composites as shown in figure 1.

It was observed from the figure 1 that stir casting and powder metallurgy techniques have the major contribution in fabrication of Al and Mg-based composites, while friction stir casting, infiltration and *in-situ* powder metallurgy have lowest contribution with their overall percentage of 4%.

This article focuses on the consequence of solid lubricant particles reinforcement on the tribological properties (such as wear coefficient and wear rate) of Mg and its alloys-based hybrid composites. The Mg-based hybrid composites reinforced with solid lubricant such as Gr, CNTs, MoS_2, WS_2, and GNPs have been studied and their wear and microstructural behaviour also examined. It was found that solid lubricants when added in Mg and its alloys results in superior wear properties due to their lubricative nature. The matrix materials, reinforcements, fabrication techniques and wear properties of different Mg-based hybrid composites developed by various authors have been summarized in table 1.

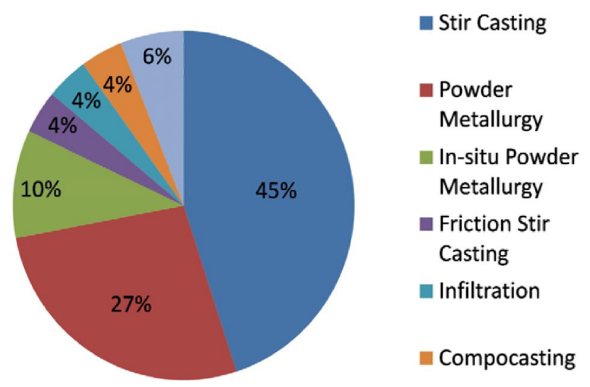

Figure 1: Percentage contribution of various fabrication processes for Al, Mg alloys and its hybrid composites adapted from Khatkar et al. [9].

Graphite Reinforced Self-lubricating Metal Matrix Composites

Aatthisugan et al. [2] prepared a AZ91D/B_4C/Gr hybrid composite by stir casting process. Their study reveals that increase in density, decrease in porosity and hardness was found when related with AZ91D alloy and AZ91D + B_4C composite. Hybrid composite to act as a self-lubricating material but also it leads to decrease in hardness, wear resistance and coef-

Table 1: Tribological behaviour and fabrication methods for different Mg hybrid composites.

S. No.	Metal matrix	Reinforcements	Fabrication technique	Wear/Tribological properties	Reference
1	AZ91D	B_4C/Gr	Stir casting	Hardness of hybrid composite increases to (22.5) than the AZ91D (20.5) BHN.	[2]
2	Pure Mg	SiC/Gr	Mechanical alloying	There was found to be 92% lower wear rate and 53% lower coefficient of friction than the matrix Mg.	[3]
3	Pure Mg	SiC/Gr	Powder metallurgy	It was found that the hardness of composite Mg/5Gr/10SiC is 77 hv that is approximately 3 times of pure Mg.	[10]
4	AZ91D	Gr/WC	Powder metallurgy	In hybrid composite there was found to be 42% rise in hardness and 19% reduction in Wear rate than Mg alloy.	[11]
5	AZ91	CNTs/B_4C	Powder metallurgy	Maximum hardness 103.2 VHN was found to be in Mg + 2% B_4C and hardness in hybrid composite of Mg + 1.5% CNTs + 0.5% B_4C was approximately 76 VHN.	[12]
6	AZ31	MWCNTs	Stir casting	Microhardness was found to increase due to CNTs concentration in aged composite from 42 HV to 50 HV compared with AZ31.	[13]
7	Pure Mg	CNTs	Disintegrated melt deposition	The matrix of Mg + 0.3% CNTs possess highest microhardness value approx. 48 beyond addition of 1.3% CNTs microhardness decreases.	[14]
8	AZ31	CNTs	Two-step process	Hardness of the composite increases with rate of 10% with addition of 0.1 vol% of CNTs and it was also found that there are finer grains than AZ31 due to presence of CNTs.	[15]
9	AZ31	CNTs	Powder metallurgy	There was found to be highest microhardness approx. 68 HV due to addition of 1 wt.% CNTs into base metal.	[16]
10	AZ31	MWCNTs	Friction stir casting	Microhardness was found to be maximum 78 HV due to the addition of MWCNTs.	[17]
11	AZ61	Al_2O_3/MOS_2	Powder metallurgy rout	In composite of AZ61 + 2% Nano Al_2O_3 + 3% Nano MOS_2 maximum microhardness in uncoated (47 HV) and coated (58 HV).	[18]
12	Pure Mg	TiC/MOS_2	Powder metallurgy	It was found that the hardness increases maximum hardness 97 VHN was found to be in composite of Mg + 10% TiC + 5% MoS_2 than the pure Mg, further addition of MoS_2 hardness decreases.	[19]
13	AZ31	SiC/WS_2	Powder processing	It was found that the average coefficient of friction was reduced to approx. 1.1 - 1.2 from 0.16 - 0.46 when compared with pure Mg.	[20]
14	Pure Mg	Zr/GNPs	Powder metallurgy	The wear rate was found to decrease by 92% when compared with pure Mg and coefficient of friction was to be 71% lower than the pure Mg at 200 μN	[21]
15	AZ91	MWCNTs/ GNPs	Semi powder metallurgy	The hardness of composite AZ91 + MWCNTs + GNPs increases approx. from 79.9 to 88.3 HN when compared with pure AZ91.	[22]

ficient of friction because of the presence of Gr reinforcement.

Al-maamari et al. [3] fabricated a hybrid composite of Mg/SiC/Gr via mechanical alloying process. they investigated that the mechanical and wear property of Mg/Gr composite was enhanced as SiC provides strength and due to Gr content composite to act as a self-lubricating material and they also examined that among the developed composites Mg + 5% SiC + 10% Gr exhibited lower wear rate and lower friction coefficient than the base and matrix Mg.

Prakash et al. [10] prepared a hybrid composite of Mg/SiC/Gr fabricated by powder metallurgy technique. It was found that the mechanical and wear property of the hybrid composite enhanced by the addition of both Gr and SiC reinforcements. As a result of integral hard ceramic nature SiC content leads to increase in the wear resistance, hardness and density of the Mg and with the addition of Gr particles into composite leads to act as self-lubricative material and further increase in Gr content the hardness of the hybrid composite decreases due to its flake structure and self-lubricating property it was found that among the other developed HMMCs the hybrid composite of Mg + 5% Gr + 10% SiC proved to be better developed composite. The reason for better wear properties was the formation of lubricant layer as shown in figure 2.

Kumar [11] fabricated a hybrid composite of AZ91D/Gr/TiC (Titanium Carbide) by compact pressing powder metallurgy process he investigated mechanical and wear property of the composite and found enhancement in the wear and hardness of the composite due to Gr and Tungsten Carbide (WC). Self- lubricating property also reflected because of the presence of Gr.

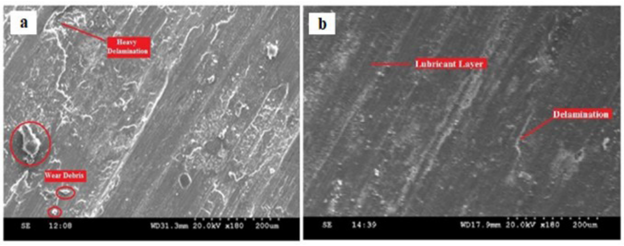

Figure 2: (a) Wear debris formed due to heavy delamination and **(b)** Lubricant layer of Gr particles adapted from Prakash et al. [10].

Carbon Nanotubes Reinforced Self-lubricating Metal Matrix Composites

Kumar et al. [12] examined microstructural and mechanical properties of AZ91 with addition of reinforcements as B_4C and CNTs was found that the compressive strength increases by addition of CNT upto1.5 wt.% and it was also found that the compressive strength decreases by adding further addition of CNTs.

Abbas et al. [13] examined the tribological performance of AZ31/MWCNTs fabricated through stir casting process. They found the hardness and wear rate increases and decreases respectively with increasing wt.% of CNTs content.

Goh et al. [14] fabricated a nanocomposite of Mg/CNTs by disintegrated melt deposition technique. Their study reveals that the physical property as tensile, yield strength, and mechanical property as ductility increases by addition of CNTs.

Han et al. [15] fabricated a composite of AZ31/CNTs by two-step process and its microstructure and mechanical properties were examined. They found that mechanical properties enhanced as Compressive yield strength increases when CNTs are added.

Sabetghadam-Isfahani et al. [16] fabricated a composite of AZ31/CNTs tungsten arc welding filler rod by powder metallurgy process. They found that with the addition of CNTs tensile strength of the material increases.

Morisada et al. [17] developed a composite of MWCNTs/AZ31 by friction stir casting process. It was found that the microhardness of the composite increases to its maximum value 78HV because of the addition of MWCNTs.

Molybdenum Disulfide Reinforced Self-lubricating Metal Matrix Composites

Victor et al. [18] fabricated AZ61/Al_2O_3/MoS_2 hybrid composite using powder metallurgy. It was found that MoS_2 lubricative particles added with AZ61 alloy act as self-lubricative material. The mechanical properties such as hardness and compressive were also enhanced by addition of MoS_2 nano particles.

Selvakumar et al. [19] fabricated a hybrid composite of MG/TiC/MoS_2 by powder metallurgy technique. Tribological properties such as wear test were done on hybrid composites and it was found that wear resistance increases by addition of 10% TiC and 7.5% MoS_2 particles.

Tungsten Disulfide Reinforced Self-lubricating Metal Matrix Composites

Zhua et al. [20] fabricated a composite of Mg/SiC/WS_2 by powder processing and found the enhancement in mechanical and tribological property as strength of the composite increases by addition of SiC and due to the addition of WS_2 wear resistance increases and coefficient of friction decreases along with its self-lubricating property also reflected by the material.

Graphene Reinforced Self-lubricating Metal Matrix Composites

Shahin et al. [21] fabricated a composite of Mg/Zr/GNPs via powder metallurgy it was found that addition of Zr increases hardness and reduces the wear and addition of GNPs further increases hardness and stiffness but also reduces the coefficient of friction and wear rate.

Turan et al. [22] developed a hybrid composite of AZ91/MWCNT/GNPs by semi-powder metallurgy it was found the enhancement in microstructure and hardness due to addition of reinforcement into AZ91 and the composite made up of AZ91 + 0.15 wt.% MWCNT + 0.15 wt.% GNPs is stable and better than other composites.

Conclusions

Mg and solid lubricant based self-lubricating hybrid composites reinforced with Gr, GNP, CNTs, MoS_2, and WS_2 have been studied and observed that dry sliding and tribological properties of Mg-based fabricated composites have been improved by addition of solid lubricants. From the brief reviews of the published research the following results have been obtained.

- The solid lubricant particles of Gr, graphene, CNTs, MoS_2, and WS_2 have huge potential for secondary reinforcement in fabricating Mg-based hybrid composites with enhanced tribological properties.
- The addition of solid lubricants results in better tribological properties by formation of lubricating layer between sliding counterparts while slight reduction in mechanical properties like hardness, impact strength can be observed.
- It was observed that stir casting and powder metallurgy techniques have the major contribution in fabrication of Al and Mg-based composites, while friction stir casting, infiltration and *in-situ* powder metallurgy have lowest involvement with their overall percentage of 4%.
- From the lecture survey presented in this article it was observed along with tribological properties most of researchers intensively researched only on few mechanical properties such as tensile strength and hardness of self-lubricating hybrid composites; while properties like toughness, flexural strength, fatigue strength, compressive strength, and creep resistance are less researched.

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Conflict of Interest

The author states that there is no conflict of interest.

Credit Author Statement

Anupam: Writing - original draft preparation, Writing - review and literature; Sandeep Kumar Khatkar: Schematic representation, Tabulation, Writing - review and editing; Pawan Kumar: Writing - review and editing; Amit Gupta: Writing - review and editing. All the authors read and approved the manuscript.

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