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Review on Wear Behavior of Magnesium Matrix Composites

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Abstract—**In the last decades, light-weight materials such as magnesium matrix composites have become hot topic for material research due to their excellent mechanical and physical properties. But relatively very less work has been done related to the wear behavior of these composites. Magnesium metal matrix composites have wide applications in automobile and aerospace sector. In this review, attempt has been done to collect the literature related to wear behavior of magnesium matrix composites fabricated through various processing techniques. Effect of different reinforcements, reinforcement content, reinforcement size, wear load, sliding speed and time have been studied by different researchers in detail. Wear mechanism under different experimental condition has been reviewed in detail. From the literature it has been observed that wear rate can be decreased with the addition of different reinforcement particles and with their varying percentage. In most of the cases wear rate increases with increase of load.**

Keywords: Magnesium matrix composites, Rreinforcement, Hardness, Wear.

I. INTRODUCTION

Magnesium and its alloys are gaining more attention now days, because of their low density and high strength to weight ratio. But, the applications of these alloys are restricted due to their low wear resistance [1]. In order to enhance wear resistance of magnesium and its alloys, magnesium matrix composites have been developed by adding various reinforcement such as SiC particles, Al_2O_3 particles, fly ash cenospheres (FAC) and TiC[2-8]. These magnesium matrix composites are preferred for many applications such as aerospace and automotive industry.Alminium matrix composites (AMCs) have also been used in specific tribologicalapplications such as brake rotors, piston rings andcylinder liners in automobiles [10]. Different fabrication methods such as stir casting, powder metallurgy, friction stir processing (FSP) and squeeze infiltration technique have been used to make these MMCs [2-8].Magnesium matrix composites (MMCs) can be a better alternative to the AMCs in near future because of their low density, high specific strength, as well as high wear resistance. In spite of the potential ofMMCs, limited work has been done. Very less literature is available related to tribological behavior of MMCs. Wear is a critical problem in the industry which leads to the replacement of engineering components. During the last decade, research has been carried out to understand the wear behaviour of AMCs but a limited work is done on MMCs. The effect of reinforcement content on wear rate, during sliding wear of MMCs has proved that the wear rate of the composite can be enhanced significantly [10]. Based on the literature survey, it has been concluded that the wear resistance is mainly affected by the reinforcement, its volume percentage, reinforcement size, applied load, sliding speed and sliding distance. Considering the potential of magnesium matrix composites as advanced wear resistant material, it is essential to review the wear behavior of different MMCs under various experimental conditions.

II. RELATED WORK OF WEAR STUDIES OF MAGNESIUM MATRIX COMPOSITES

Gertsberg et al. [2] fabricated AZ91/SiC magnesium matrix composites using high-pressure die casting. AZ91D ingots were melted in steel crucible up to 640 ^{0}C under the protection atmosphere of 99.5% CO_2 + 0.5% SF_6.Preheated 700^0 C SiC reinforcement particles were added through spill immersed in the melt. After the addition of the particles while stirring the melt, the stirring was stopped and the melt was held for 2 h in order to enhance wetting between particles and melt. Following this the stirring was resumed for 15 min again. The wear tests on MMC were conducted on a block-on ring type wear resistance testing machine using sliding speed 300 rpm, sliding time 60 min and loads 5-120 N. The weight losses before and after wear test were calculated. The wear surfaces of composite showed that at high loads the material removed from the surface of composite specimens occurred due to the higher level of porosity, while the worn surfaces of base metal were relatively smoother.

Yu and Huang [3] investigated the effects of the applied load, the wear time, diameter and the fly ash cenosphere (FAC) content on the wear behavior of the AZ91D/ fly ash cenosphere composites fabricated through stir casting method. Four different diameters of FAC ie. 40, 80,100 and 150μm were used for composite fabrication.Wear tests were performed on pin-on-disk wear test machine under dry sliding condition. The rotational speed of the disk used was 60 rpm. The applied load was 5, 10, 20, and 30 N, respectively and the wearing time was 10, 20, 30, and 50 min, respectively. Results indicated that AZ91D/ 6 wt.% FAC composites were more wear resistant than AZ91D under above testing conditions.

Under the same applied load, the wear resistance of the composites is excellent when FAC diameter is moderate ie 100μm. If FAC diameter is more than 100um the wear of the composites decreased again. The wear resistance of the composites decreased with the increase in the applied load.

Nonlinear relationship was observed between the worn mass loss and the applied load. The mass fraction of FAC in the composites has also important effect on the wear resistance of the composites. With the increase in the mass fraction of FAC worn mass loss of composites decreased. The wear resistance of the composites is excellent when the mass fraction of FAC is 6 Wt.% which is also confirmed from surface morphology of composite.

Abbasi et al. [4] developed surface composites on the surface of AZ91 magnesium alloy by application of FSP. Two types of surface composites were prepared using SiC and Al_2O_3 particles separately as reinforcements. The results showed that wear properties of FSPed samples were better than AZ91. The results indicated that by increment of FSP pass upto 4 number wear rate decreased. The results also showed that particle type did not have significant effect on wear rate. Microscopic images show that grooves in base metal are deeper than those in processed samples. This can be correlated to the lower hardness of as-received material as compared to processed samples.

Chen et al. [5] successfullyprepared a surface composite layer reinforced by SiC particles on the thixoformed (TF) AZ91D alloy by FSP and the corresponding tribological properties were investigated. The microstructural evolution of the thermomechanically affected zone (TMAZ) could be clearly observed during FSP of the thixoformed AZ91D alloy. The main mechanisms of grain refinement during FSP include thermodynamic recrystallization and mechanical separation. The thixoformed AZ91D alloy with the composite surface possessed good tribological properties which were because of the presence of SiCp. Compared with the corresponding permanent mould casting alloy and the TF alloy without composite surface, the composite surface showed the highest wear resistance and lowest friction coefficient.

Reddy et al. [6] fabricated surface composites using friction stir processing. ZM21 magnesium alloy was used as matrix. Silicon carbide and boron carbide powders are used as reinforcement. Composites were characterized by metallography, hardness and pin-on-disc testing. Results show fine and uniform distribution of carbide particles in Mg matrix. Processed composites exhibited excellent wear resistance and which was attributed to grain boundary pinning and dispersion hardening caused by carbide particles. Composite prepared with boron carbide was found to possess better wear resistance than composites made with silicon carbide. This was attributed to formation of very hard surface layer of boron carbide reinforced composite. The wear behaviour of surface composite layer on ZM21 Mg alloy with that of conventionally used engineering materials such as mild steel and austenitic stainless steel was also compared. Jo et al. [7] investigated the effect of SiC particle size on the wear properties of AZ91 hybrid metal matrix composites reinforced with Saffil short fibers and SiC particles prepared through squeeze infiltration process. Different particle sizes of SiC 1, 7, and 20 µm, respectively, were used. The volume fractions of Saffil short fibers and SiC particles used in the hybrid composites fabrication were 15 and 5%, respectively. Ball-on disk wear test were conducted under loads of 5, 15, and 30 N and at sliding speeds of 0.1 and 0.2 m/s. The results indicated that the composite reinforced with large-sized SiC particles had better wear resistance compared with the smaller sized particles. At a low sliding speed and under lower loads of 5 and 15 N, the dominant wear mechanism of the composites observed was abrasive/adhesive. With the increase of load to 30 N a transition from abrasive/adhesive to severe abrasive wear occurred. A mechanically mixed layer was formed on the surface of the composite, at a higher sliding speed, which helped to increase wear resistance of the hybrid composites. The main mechanism under this condition was delamination wear. The effect of SiC particle size on wear properties in composites was found to be negligible under conditions of abrasive/adhesive or delamination wear mechanisms. However, the wear behavior of composites was largely influenced by their SiC particle size when the abrasive mechanism was severe.

Narayanasamy et al. [8] studied the effect of hybridizing MoS_2 on the tribological behavior of Mg–TiC Composites. A magnesium–TiC–MoS2 hybrid composite was developed by powder metallurgy route. The results indicated that the Mg–TiC–MoS_2 hybrid composites possess better hardness, higher wear resistance and lower coefficient of friction when compared with Mg, Mg–TiC and Mg–MoS_2 composites. The increase in hardness was attributed to the presence of hard TiC particles. Hardness was slightly decreased with addition of MoS2 when compared to Mg–TiC composite. The wear behaviors of these composites were investigated by pin-on-disc wear testing apparatus under dry sliding condition. The wear resistance of the composites improved considerably as compared to that of the magnesium matrix due to the courteous effect of both the reinforcements. The best tribiological performance was seen in composite with 10 wt% TiC and 5 wt% MoS_2. It was observed that wear loss and coefficient of friction increased with increase of either load or sliding distance or both, whereas wear loss and coefficient of friction decreased with increase of speed. The worn surfaces of various composites showed that abrasive wear and delamination were the major wear mechanisms.

Huang et al. [9] studied the effects of silicon carbide particle size on wear behavior of AZ91D /SiCp composite prepared by the melt stirring technique. Results indicated that the of SiC

TABLE1: SUMMARY OF RESEARCH WORK DONE BY VARIOUS RESEARCHERS' RELATED TO WEAR OF MAGNESIUM MATRIX COMPOSITES

S. NO.	INVESTIGATORS	MATRIX USED	REINFORCEMENT USED	TECHNIQUE USED	IMPORTANT RESULTS
1.	Gertsberg et al. [2]	AZ91D	SiC average particle size 10 µm 5 and 10 wt.%	high-pressure die casting	• Lesser wear rate of reinforced composites in comparsion to unreinforced alloy. • Increase in wear rate with increase of load.
2.	Yu and Huang [3]	AZ91D	Fly ash cenosphere 6 wt.%	Stir casting	• Better wear resistance of fabricated composites in comparsion to Mg alloy. • Excellent wear resistance of the composites achieved with moderate FAC diameter. • Wear resistance of the composites decreased with the increase in the applied load.
3.	Abbasi et al. [4]	AZ91	SiC 30 nm. Al2O3 30 nm.	FSP	• Wear rate of base metal found greater than other composites. • With increase in FSP pass hardness increases which lead to decrease in wear rate. • Processed composites using SiC and Al_2O_3 particles have nearly the same wear resistance.
4.	Chen et al.[5]	AZ91D	SiC	Permanent mould casting FSP composites	• Good tribological properties obtained in the composite surface of thixoformed AZ91D alloy. • The friction coefficient and wear rate found to be minimum in case of surface composite as compared to permanent mould casting, thixoformed alloy. • For surfaced composites increase in hardness lead to decrease in wear rate.
5.	Reddy et al. [6]	ZM21	SiC and B4C	Friction stir processing (FSP)	• Surface composites prepared with B4C obtained superior wear resistant as compared to those made with silicon carbide. • Improvement in the hardness of composite layer with the addition of carbides. • FSP with boron carbide powder significantly improved the wear resistance over the base metal.
6.	Jo et al. [7]	AZ91	Saffil short fibers SiC particles particle sizes of 1, 7, and 20 µm 15 and 5%	Squeeze infiltration	• At low sliding speed and loading conditions, the dominant wear mechanism of the hybrid composites was found to be abrasive/adhesive. • With increase of load, mechanism changed from abrasive/adhesive to severe abrasive. • At a high sliding speed, wear resistance of the hybrid composites increased and wear mechanism involved in this condition was delamination wear. • No effect of SiC particle size on wear properties in composites.
7.	Narayanasamy et al. [8]	magnesium powder (99.8 % purity)	TiC and MoS_2	Powder metallurgy	• Hybrid composites Mg–TiC–MoS_2 possess better hardness and higher wear resistance as compared to Mg, Mg–TiC and Mg–MoS_2 composites. • Best tribological performance of composite observed at 10 wt% TiC and 5 wt% MoS_2. • Abrasive wear and delamination are the major wear mechanisms seen on worn surface of composites.
8.	Huang et al. [9]	AZ91D	SiC volume fraction of 3% 5, 11, and 15 lm	Melt-stirring	• Improved in wear resistance with the addition of SiC. • The coefficient of friction increased with increasing particle size of SiC. • The specific wear rate decreased with increasing particle size of SiC. • Under different load, wear mechanism of composites was abrasion, oxidation, and delamination.

9.	Xiu et al. [10]	AZ91	5, 10 and 15 wt.% TiC	TiCp–Al master alloy process combined with mechanical stirring.	• Hardness and wear resistance of the composites improved significantly as compared to base metal. • The wear resistance of the composite increased with increase of the TiC content. • Wear volume loss increased with increase of applied loads or wearing time. • The wear mechanism was mainly ploughing, adhesion and oxidation.
10.	Yao et al. [11]	AZ91	TiC	Spray deposition.	• Wear resistance of composites improved with the addition of TiC. • At a lower load, wear rate of composites decreased with increasing TiC content, and the dominant wear mechanism was oxidation. • At a higher load, Mg composites showed excellent wear resistance and the dominant wear mechanism was delamination.
11.	Saravanan and Surappa [12]	Pure magnesium	SiC 30 Vol.%	Melt stir technique	• Cast composites showed significant decrease in wear rate in comparison to pure Mg
12.	Asadi et al. [13]	AZ91	nanosizedSiC and Al2O3 particles	FSP	• Increase in wear resistance in composites as compared to the base metal. • Better wear resistance obtained with SiC reinforcement.. • Wear mechanism was twofold in specimen reinforced with SiC particles, while in the specimen with Al_2O_3 particles, delamination wear occurred.

addition could improve the wear resistance of AZ91D matrix alloy for most of the sliding conditions. The superior wear resistance was exhibited under lower and moderate sliding condition. The hardness of composites after wear tests was measured and observed that it increased with increasing particle size of SiC both for 10 and 50 N loading conditions at low sliding speed of 250, 1000, and 1500 rpm. The specific wear rate decreased with increasing particle size of SiC for moderate sliding conditions at any specific sliding speed of 250 and 1000 rpm, except for 10 and 50 N at the severe sliding condition of 1500 rpm. The wear mechanism under 10N load was moderate abrasion, moderate oxidation, and slight delamination and slight abrasion, moderate oxidation, heavy delamination, and moderate adhesion and moderate softening/melting types for load of 50 N.

Xiu et al. [10] investigated the the sliding wear behavior of TiC/AZ91 magnesium matrix composites. Different weight % of TiC (5, 10 and 15 wt.%) particulates were used to fabricate TiCp–Al master alloy process combined with mechanical stirring. The effect of TiC particulate content, applied load and wearing time on the sliding wear property of the composites was studied. Results indicate that the hardness and wear resistance of the composites improved significantly as compared to AZ91 alloy. The wear resistance of the composites increases with increase of the reinforcement content, on the other hand friction coefficient of the composites decreased with increase of reinforcement content. The wear volume loss and friction coefficient of the composites as well as the base material increased with increase of applied load or wearing time, but the increase rates of the reinforced composites in two performance was found to be lower than those of the unreinforced AZ91 matrix alloy. Wear behavior mechanism observed in the unreinforced AZ91 matrix alloy and the composites was ploughing, adhesion and oxidation.

Yao et al. [11] studied wear mechanism of TiC particles reinforced AZ91 magnesium matrix composites fabricated by a melt in situ reaction spray deposition method. The dry sliding wear tests were performed under different load conditions 10, 20, 30, 40, and 50 N. Results showed that the composites had much better wear-resistance than the AZ91 alloy. The wear behavior of the composites was dependent on the TiC content in the matrix and the applied load. At a minimum load, the wear rate of fabricated composites decreased with increasing TiC content, and the dominant wear mechanism was an oxidative mechanism. At maximum loads, composites exhibited superior wear resistance to the AZ91 magnesium alloy, and the dominant wear mechanism involved was delamination.

Saravanan and Surappa [12] fabricated pure magnesium-30 vol.% SiC particle composite by melt stir technique without the use of a flux or protective atmosphere. Hot extrusion was done on cast composites with an extrusion ratio of 13. Pin-on disc machine was used for wear testing under loads in the range 5–50 N and at a sliding speed of 0.5 m/s. Results indicate that Magnesium composites show a wear rate lower by two orders of magnitude when compared to pure Mg. Improvement in wear resistance was attributed to the presence of SiC particles and to the improved strength of the composite.

Asadi et al. [13] studied the effects of particle types and number of friction stir processing passes on the magnesium-based nanocomposite produced by Friction Stir Processing. Two different nanosized particulate reinforcements (SiC and Al_2O_3) were added to as-cast AZ91 magnesium alloy.Thenanocomposite prepared with SiC particles showed smaller grain size and higher hardness and wear resistance in comparison to nanocomposites prepared with Al_2O_3 particles. The wear resistance increased with the addition of reinforcing particles. In the composites fabricated with SiC particles, the wear mechanism is twofold, while in the composites with Al_2O_3 particles, delamination occurs due to the low integrity between alumina clusters and the magnesium matrix. Results showed that with the increase in FSP passes hardness and wear resistance improved due to grain refinement. Table1. has been prepared for quick review of the wear studies related to magnesium matrix composites.

III. CONCLUSIONS

Magnesium matrix composites have become excellent material in comparison to magnesium and its magnesium alloys. In last decades, some studies have been carried out to understand microstructure and mechanical properties of these composites to prop up their application in the automobile and aerospace industries. However, very less effort have been done to understand wear behavior of these composites. In this paper wear behavior of magnesium matrix composites fabricated using different techniques has been reviewed. From above studies it was concluded that wear rate of composites can be improved with the addition of different reinforcements such as SiC, Al2O3, TiC, FAC and B4C. In most of the cases wear rate increased with increase of load except for flyash reinforcement, in which a marginal decrease in wear was observed by the researcher. The wear resistance of the composite increased with increase of the reinforcement content in general. In surface composites with increase in FSP pass hardness increased which further lead to decrease in wear rate. Under different wear conditions dominant wear mechanisms observed in different composites was abrasive/adhesive, oxidation, and delamination. Hence it may be concluded that Mg matrix composites can be used for specific applications in automotive sector where wear resistance is major concern.

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