Journal of Science: Advanced Materials and Devices 5 (2020) 535–544

Contents lists available at ScienceDirect

Journal of Science: Advanced Materials and Devices

journal homepage: www.elsevier.com/locate/jsamd

Original Article

Mechanical and tribological characterization of self-lubricating Mg-SiC-Gr hybrid metal matrix composite (MMC) fabricated via mechanical alloying

Azzat Esam Abdulqader Al-maamari, AKM Asif Iqbal*, Dewan Muhammad Nuruzzaman

Faculty of Manufacturing and Mechatronic Engineering Technology, Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia

ARTICLE INFO

Article history:
Received 19 March 2020
Received in revised form
23 August 2020
Accepted 4 September 2020
Available online 10 September 2020

Keywords:
Metal-matrix composites (MMCs)
Characterization
Mechanical properties
Wear
Mechanical alloying

ABSTRACT

This study deals with the fabrication and tribo-mechanical characterization of magnesium (Mg)-silicon carbide (SiC)- graphite (Gr) hybrid metal matrix composites (MMCs). The hybrid MMCs were fabricated by a mechanical alloying process and their mechanical and tribological properties were investigated as well as compared with those of the base material and the Mg-Gr composite. The morphology analysis of the constituent powders and the hybrid powder mixture was conducted through SEM, EDX and XRD. The microstructure of the sintered MMCs showed a uniform distribution of the reinforcement on the matrix. The developed hybrid MMCs exhibited greater mechanical properties when compared to the base material and the Mg-Gr composite. The tribological characterization of the fabricated hybrid MMCs was studied using the pin-on-disc tribometer under dry sliding conditions. The hybrid MMC composed of 5% Gr and 10%SiC (Mg+5%Gr+10%SiC) demonstrates 92% low wear rate and 53% low friction coefficient than the matrix Mg. Therefore, this hybrid MMC can be a potential candidate to develop components used in the tribological operation.

1. Introduction

Weight reduction is considered as one of the important factors for improving energy efficiency while developing high-performance automobiles and space crafts. This motivates automotive and aerospace industries to design novel advanced lightweight materials with enhanced mechanical and functional properties [1]. In the past decades, aluminium and its alloys were proved to be the most reliable lightweight materials and they were used significantly on producing components of automobiles and space vehicles [1,2]. In recent years, magnesium (Mg) and its alloys have immerged as the potential candidate for lightweight applications as magnesium possesses lower density compared to aluminium. Particularly, magnesium is the lightest structural metal which is 33% lighter than aluminium, 61% lighter than titanium and 77% lighter than steel that makes Mg the best alternative choice to these metals [2]. Unfortunately, high oxidation rate and low wear resistance are few of the drawbacks that restrict the use of Mg alloys in service conditions [3,4]. However, these limitations can be overcome by using magnesium-based metal matrix composites. Usually, the metal matrix composites (MMCs) exhibit improved wear resistance over the monolithic materials and their wear performance can further be improved by incorporating Graphite (Gr) and Molybdenum disulphide (MoS_2) which demonstrate self-lubricating property. Graphite is a widely accepted self-lubricating material that possesses a layer-lattice structure in which the layers consist of flat sheets of atoms or molecules. This helps the materials to shear parallel to the layers than across them [5,6]. Due to this unique property of graphite, a continuous layer of graphite solid lubricant is formed on the tribosurface of the metal-graphite composite during the dry sliding condition that reduces plastic deformation and prevents metal-to-metal contact between the two sliding surfaces, hence, reducing friction and improving the wear resistance of the composite [7,8].

It was reported previously that a small amount of graphite addition to the metal-ceramic composite extremely improves the wear resistance and reduces the friction coefficient. Aatthisugan et al. [2] investigated the wear behavior of magnesium AZ91D-Gr composite and found that only 1.5% addition of Gr significantly improved the wear resistance of the composite. The same phenomenon was also observed by Deaquino et al. [9] while investigating the tribological behavior of Al7075-Gr composite. The authors fabricated the composite by mechanical milling and found

* Corresponding author.
E-mail address: asifiqbal@ump.edu.my (A.A. Iqbal).
Peer review under responsibility of Vietnam National University, Hanoi.

https://doi.org/10.1016/j.jsamd.2020.09.002

that only 1.5% of Gr addition tremendously improved the wear resistance of the composite. Further, Lokesh and Mallik [10] used Taguchi technique and evaluated the relationship between the wear rate and the applied load and sliding distance while investigating the wear behavior of the stir-cast Al-3%Gr composite. They reported that the wear rate was strongly influenced by the applied load. Although the addition of graphite produced a remarkable wear performance in the MMCs, however, it was reported that using graphite drastically reduces the mechanical properties of these materials [11–13]. This property degradation restricts the use of the graphite reinforced MMCs in structural applications. To overcome this problem, a solution could be to incorporate a third ceramic particle such as SiC or Al_2O_3 in graphite-reinforced MMCs and make a hybrid composite. This strategy could be useful to compensate for the weakening effects caused by the graphite and to enhance the overall mechanical properties of the composite required in developing structural components. Few studies have investigated this approach in order to obtain improved different mechanical and tribological properties together in a single hybrid material. Aatthisugan et al. [2] developed a boron carbide (B_4C) and Gr reinforced magnesium AZ91D hybrid composite by the stir-casting method and investigated the mechanical and wear properties. They have reported that the addition of 1.5% B_4C and 1.5% Gr to the magnesium alloy significantly improved the hardness and tensile strength of the hybrid MMC. Besides, Zhang et al. [14] investigated the microstructure and mechanical properties of carbon nanotube (CNT) reinforced AZ91D magnesium matrix composite. Tremendous improvement of yield strength and ultimate tensile strength was reported by the authors.

Moreover, a uniform dispersion of reinforcing particles throughout the matrix is one of the prime requirements for enhancing the mechanical properties of MMCs [15]. Non-uniform particle distribution develops the agglomeration and clustering of particles in the matrix surface which eventually becomes a vulnerable site of crack initiation, thus degrades the overall mechanical properties of the MMCs. In general, the MMCs produced by the conventional casting process exhibit poor wettability between the reinforcement and the matrix, and develop the intermetallic compounds, accompanied by the porosity at the particle-matrix interfaces [16–18]. In addition, the reinforcement's non-uniformity issue always encounters in the casting process. Hence, to obtain a uniform particle distribution, several techniques have been employed. Mula et al. [19] used an ultrasonic method to achieve a uniform distribution of reinforcement in the Al and Mg matrix alloy. But, this process is expensive and difficult to produce in large scale. Among the various production techniques, mechanical alloying is considered as one of the effective alternative processes to fabricate MMCs. This technique offers a uniform dispersion of the reinforcing particles over the matrix material, thus, ensures excellent mechanical and wear properties [9]. Additionally, this process is chemically non-reactive and it facilitates the fabrication of MMCs with high reinforcement contents [20]. Although the mechanical alloying process exhibits some superior quality, however, the production of the graphite and SiC reinforced magnesium hybrid MMC by using mechanical alloying have rarely reported and thus the present study aims to fabricate a hybrid MMC by mechanical alloying process and to evaluate their mechanical and tribological properties.

2. Experimental

2.1. Fabrication of hybrid MMCs

In this study, magnesium powders with 99% purity and average particle size of 100 μm were used as the matrix material, whereas SiC powders (purity 99%) and graphite powders (purity 99%) with the average particle size of 74 μm and 40 μm, respectively, were used as the reinforcements. According to a previous study, the addition of 5% Gr to the Mg matrix exhibits superior wear properties [12]. Thus, in this study the percentage of Gr powder was kept constant while the percentage of SiC had been varied. The different compositions of the elemental powders to prepare the hybrid MMCs are shown in Table 1. The elemental powders were weighted carefully using a digital balance and then mixed in a high-energy planetary ball mill (Model: RETSCH PM 100) to obtain the uniform powder mixture. To avoid the agglomeration of the powder, a process control agent, Polyvinyl alcohol (PVA) was applied (in the ratio of 2% of the powder mass) to the powder mixture. The milling was performed for 1 h with a rotational speed of 100 rpm at room temperature to ensure the uniformity of the mixture. After that the powder mixture was examined by using Scanning Electron Microscopy (SEM) (JOEL model 6390). The SEM micrograph of the as-received magnesium, SiC, graphite powders and the mixture of the hybrid powder are shown in Fig. 1. It is clearly noted in the SEM micrograph that the Mg particles have the spherical and ellipsoidal shape, the SiC particles look like of the cubic and cuboid shape and the graphite particles show a shape of flakes. The reinforcement SiC and graphite particles are found arranged uniformly in the Mg matrix as shown in Fig. 1(g, h). The magnesium powders are porous in nature and few big macro-agglomerations in the Mg powders are observed in the SEM analysis as indicated by the dotted circles in Fig. 1(b, g, h).

The existence of the macro-agglomerations may influence the mechanical properties of the material as these may contain a certain porosity. X-ray diffraction (XRD) was carried out in all the elemental powders and the powder mixture to evaluate the structural phases using a high-resolution X-ray diffractometer (Shimadzu XRD 6000) and the XRD patterns are shown in Fig. 2. The obtained Bragg angles were matched with standard values for Mg, SiC, and Gr. The XRD pattern shows high-intensity Mg, Si and carbon characteristic peaks indicating the presence of Mg, SiC and Gr in the powder mixture. For further investigation, the hybrid powder mixture was analysed by the EDX spectra shown in Fig. 3 to study the presence of different elements in the composites. The EDX spectrum clearly shows the magnesium, silicon, carbon and oxygen characteristic peaks and their weight percentage in the indicated position (Spectrum 3). After the mixing process, the mixture of the Mg–SiC-Gr elemental powders was heated in a vacuum oven up to 100 °C for 1 h to evaporate the volatile matter in the mixture. The compaction of the mixed hybrid powders was carried out at room temperature in a single-die uniaxial hydraulic press (TOYO: Model TL30, capacity: 300 kN) with a nominal force of 250 kN. The load on the powder mixture was maintained for 30s and then released. Subsequently, the green compact specimen was prepared. Zinc stearate was used in the die wall as a lubricating agent and was applied manually before each compaction process. After compaction, the sintering of the samples was carried out in a vacuum sintering furnace (BSO-1200G) at 550 °C temperature. The samples were then cooled in the furnace and prepared for subsequent mechanical and wear tests. The sintered cylindrical and tensile specimens are illustrated in Fig. 4.

Table 1
Composition of magnesium (Mg), SiC and graphite (Gr) for hybrid MMCs.

Sample	% of Mg	% of SiC	% of Gr
S1	100	0	0
S2	95	0	5
S3	85	10	5
S4	80	15	5
S5	75	20	5

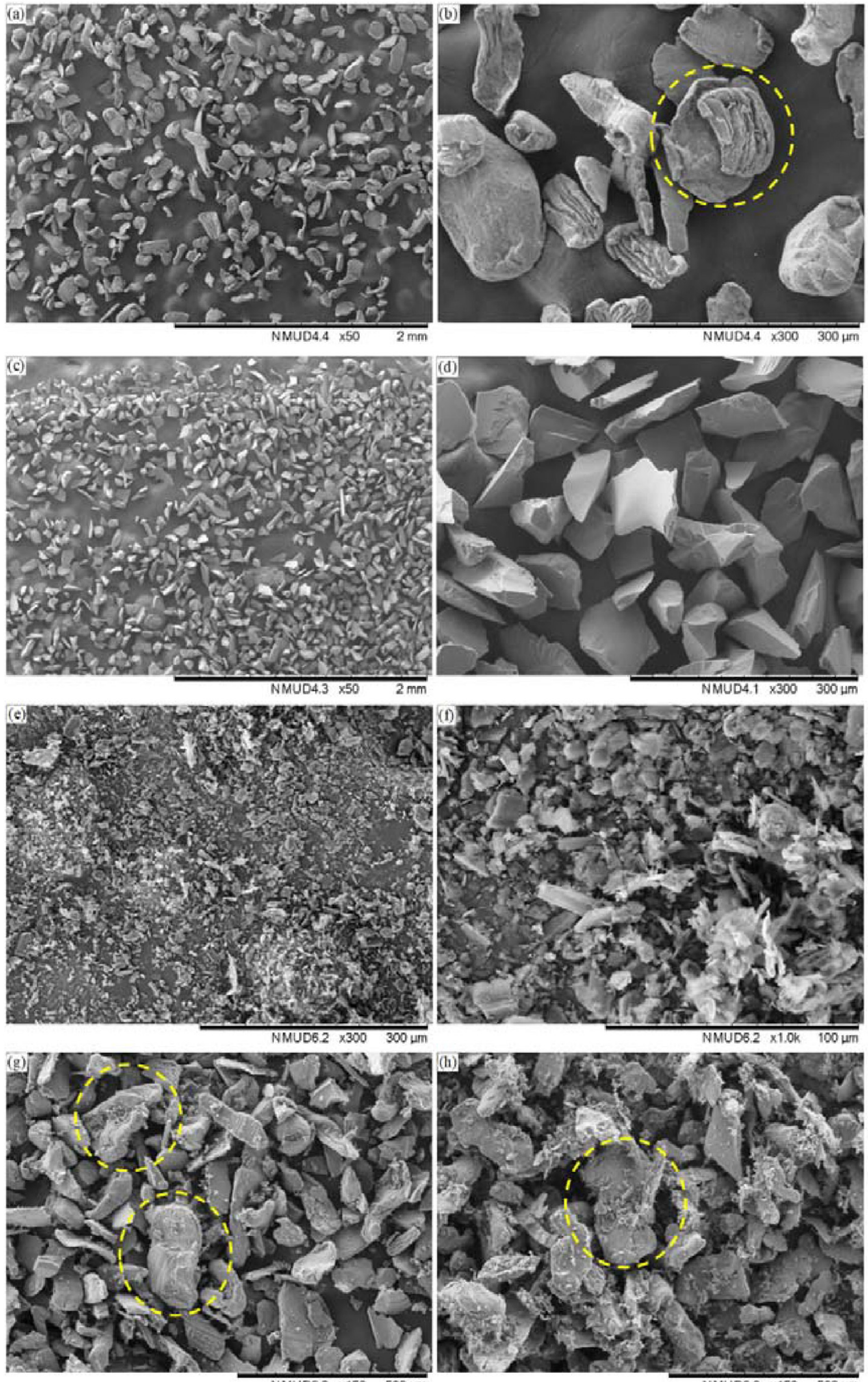

Fig. 1. SEM images of (a) (b) Mg powder, (c) (d) SiC powder, (e) (f) Gr powder (g) (h) Mg+5%Gr+15%SiC powder mixture.

2.2. Microstructure observation

To investigate the distribution of the SiC and Gr particles in the magnesium matrix, microstructural characterization studies were performed on the top surface of all the fabricated hybrid MMC samples by optical microscopy (OLYMPUS BX51M, Made in Japan) and SEM (JOEL model 6390). The samples were consecutively polished with conventional abrasive papers of grades 1500, 2000 and 2500 to remove scratches and surface machining marks. Finally, the samples were polished using 3 μm and 1 μm diamond paste suspended in distilled water in a mechanical polishing machine in order to obtain a mirror-like surface finish. These polished samples

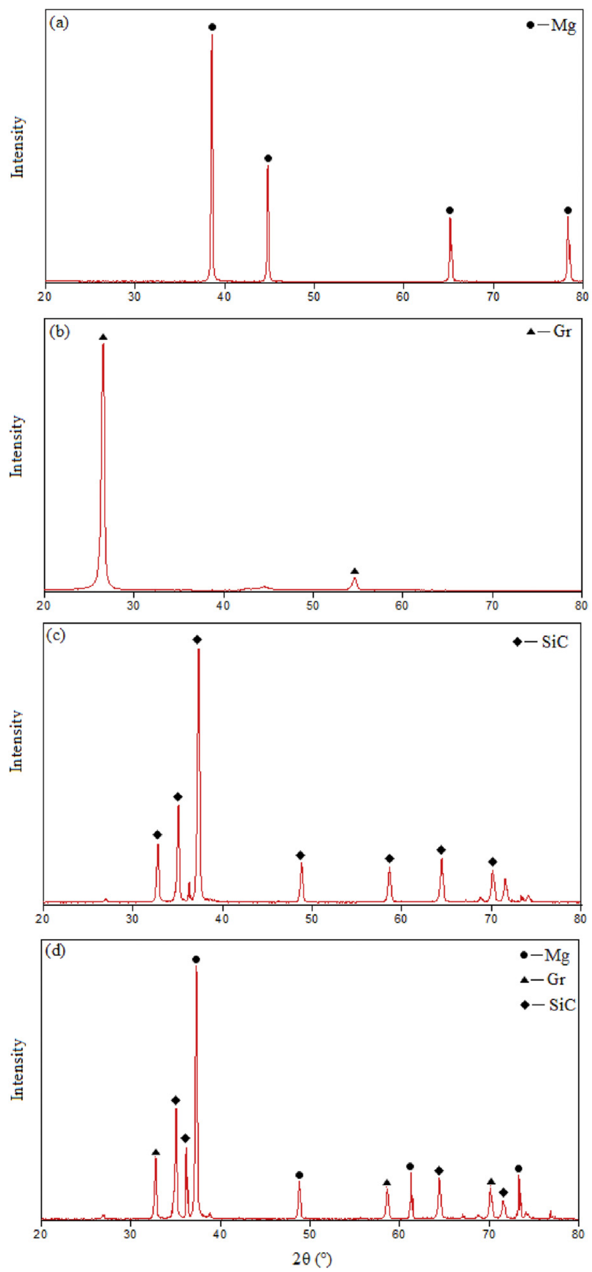

Fig. 2. XRD patterns of (a) Mg powder (b) Gr powder (c) SiC powder (d) Mg+5% Gr+15%SiC powder mixture.

were used for microstructural characterization and different mechanical testing.

2.3. Hardness measurement

The hardness of the pure Mg and the prepared hybrid MMCs was measured by using a Vickers hardness tester (Wilson Hardness: Model 402 MVD, Made in USA). The tests were performed at room temperature and according to the guidelines of ASTM E384. A load of 300 gf (2.94 N) was applied to all the specimens for a duration of 20s. A diamond-shaped indenter was used for the indentation and by measuring the indentation marks with the built-in scale in the hardness tester, the hardness value was obtained. Ten measurements were taken on the polished surface of each specimen with an interval of 1 mm to avoid any influence of the adjacent indentations and the mean value was taken as the Vickers hardness (HV) value.

2.4. Tensile and flexural strength test

The uniaxial tension tests were carried out at room temperature in a universal testing machine (INSTRON 3369) as per the guidelines specified in ASTM E8-08. A load cell of 100 kN was applied to the specimens with a displacement rate of 0.016 mm/s and the tensile properties of the hybrid MMCs were explored by the obtained stress–strain diagram. Besides, the flexural strength of the hybrid MMCs was investigated by a typical three-point bending test as per ASTM E855-08. A 100 kN load cell was used and a constant displacement rate of 1 mm/min was maintained. Finally, the load and deflection data was recorded and the bending stress was calculated by using the following equation:

$$\sigma_B = \frac{3\,PL}{2bh^2} \tag{1}$$

2.5. Tribology test

The dry sliding wear behavior of all the fabricated samples was investigated using a pin-on-disc tribometer according to the ASTM G99-05 standard. The cylindrical-shaped pellet specimens with 40 mm diameter and 4 mm thickness were prepared for the wear tests. The samples were placed on the disc of the tribometer and the pin was rotated against the samples. The specimens and the pins were cleaned with acetone before and after each run of the wear test to remove the trace contaminants. The tests were conducted with variable loads of 10, 20 and 30 N loads and variable sliding speed of 0.5, 0.8 and 1 m/s in order to investigate the relationship of the wear rate with the loads and the sliding speeds. The specific wear rates were measured by using the weight loss method. A digital weighing balance with the accuracy of ±0.1 mg was used to measure the weight loss. Moreover, the coefficient of friction of all the hybrid MMC specimens was measured with a constant load of 10 N and a constant linear speed of 15 cm/s. After the wear tests, the morphology of the worn surface of each sample was examined by SEM (JOEL model 6390) to analyse the wear mechanisms in the hybrid MMCs.

3. Results and discussion

3.1. Microstructure analysis

Fig. 5 illustrates the optical and SEM micrographs of the fabricated hybrid MMCs. The white area in the optical micrographs represents the Mg matrix and the SiC and Gr reinforcement particles are indicated in the figure. It is clearly visible that the reinforcement particles are distributed uniformly in the matrix material in all the samples. Previous studies reported that the uniform dispersion of reinforcement on the matrix surface is one of the key factors to obtain improved mechanical and tribological properties in the MMCs [9,12]. Besides, the bonding between the matrix and the reinforcements seems perfect and other anomalies such as pores and cracks are almost absent in the microstructures observed optically. These phenomena noticed in the optical micrographs indicate an achievement of a proper sample fabrication. Moreover, to investigate any micro-level anomalies, SEM analysis was performed in the microstructure and the micrographs are also presented in Fig. 5. The SEM micrographs revealed few pores and cracks on the surface of the fabricated hybrid MMC samples as

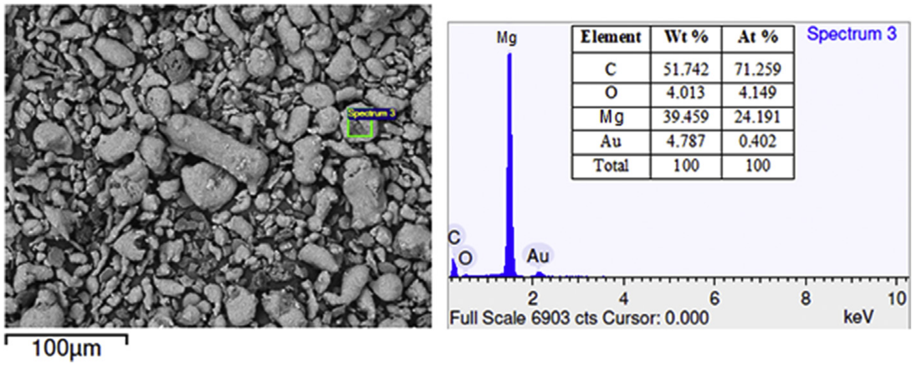

Fig. 3. SEM image and EDX analysis of Mg+5%Gr+15%SiC hybrid powder mixture.

indicated in the figure. However, the diameter of the pores is very small, less than 2 µm and the length of the microcracks is less than 20 µm which is highly insignificant. Therefore, it can be concluded that the uniform particle distribution and the strong particle-matrix interfacial bonding are achieved in all the hybrid MMC samples during the fabrication process which can lead to improved mechanical and tribological properties.

3.2. Mechanical properties

Table 2 represents the values of the various mechanical properties of the fabricated self-lubricating hybrid MMC samples. Among all the tested materials, the composite composed of only Gr particles (Sample S2) exhibits the lowest hardness value. This phenomenon was also observed in the previous study which reported that the addition of graphite to the pure Mg reduces the hardness of the composite [12]. However, the addition of SiC particles results in an increase in the hardness value of the Mg-Gr composite. The higher the volume percentage of the SiC particles the greater the hardness value is observed in the hybrid MMCs. Among the five samples, the highest hardness value was observed in the sample S5 which is composed of 20% SiC particles. This hybrid MMC shows around 138% and 82% enhancement of the hardness as compared to the Mg+5%Gr composite and the pure Mg material, respectively. Besides, the other two composite samples S3 and S4 which are fabricated with 10% SiC and 15% SiC display around 65% and 96% hardness increment from that of the Mg+5%Gr composite and 26% and 50% hardness augmentation as compared to that of pure Mg. Graphite possesses low hardness value of 25.49 HV. Thus, its addition to the pure monolithic Mg reduces the overall hardness of the composite. In contrary, the ceramic SiC particles are very hard, therefore their addition to the Mg+5%Gr results in an increase of the overall hardness of the hybrid MMC.

Moreover, the tensile behaviour of all the fabricated samples is presented in the stress–strain diagram as shown in Fig. 6 and the result of the tensile strength measurement is shown in Table 2. It is observed that the composite reinforced with only graphite particles (Sample S2: Mg+5%Gr) exhibits a lower value of tensile strength than that of the pure matrix material and this behavior has been explained in detail in our previous research [12]. In this study, a tremendous enhancement of the tensile strength is achieved in all the hybrid MMCs once SiC particles are added to the Mg+5%Gr. Among the three compositions of the hybrid MMCs, the maximum strength is observed in the sample S5 (Mg+5%Gr+20%SiC) which exhibits around 38% increase in the tensile strength compared to the Mg+5%Gr composite and 26% in comparison to the pure Mg.

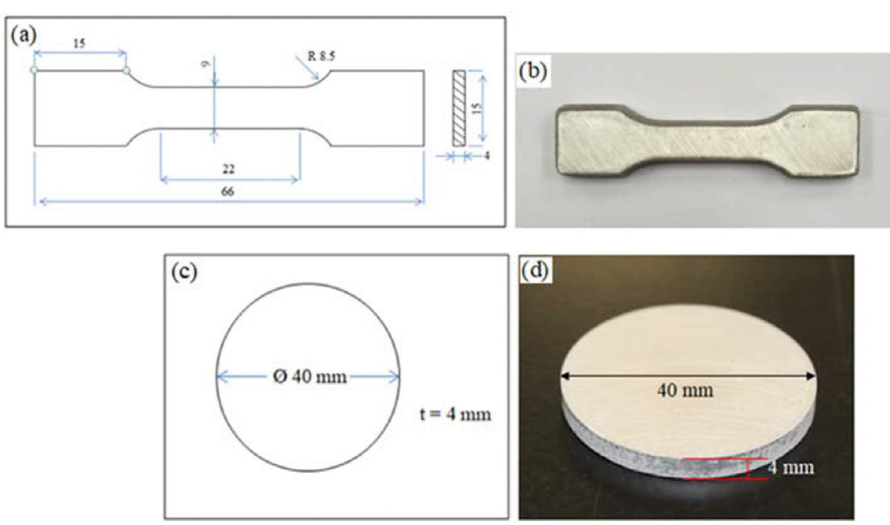

Fig. 4. Schematic diagram and photograph of (a) (b) tensile specimen and (c) (d) cylindrical specimen.

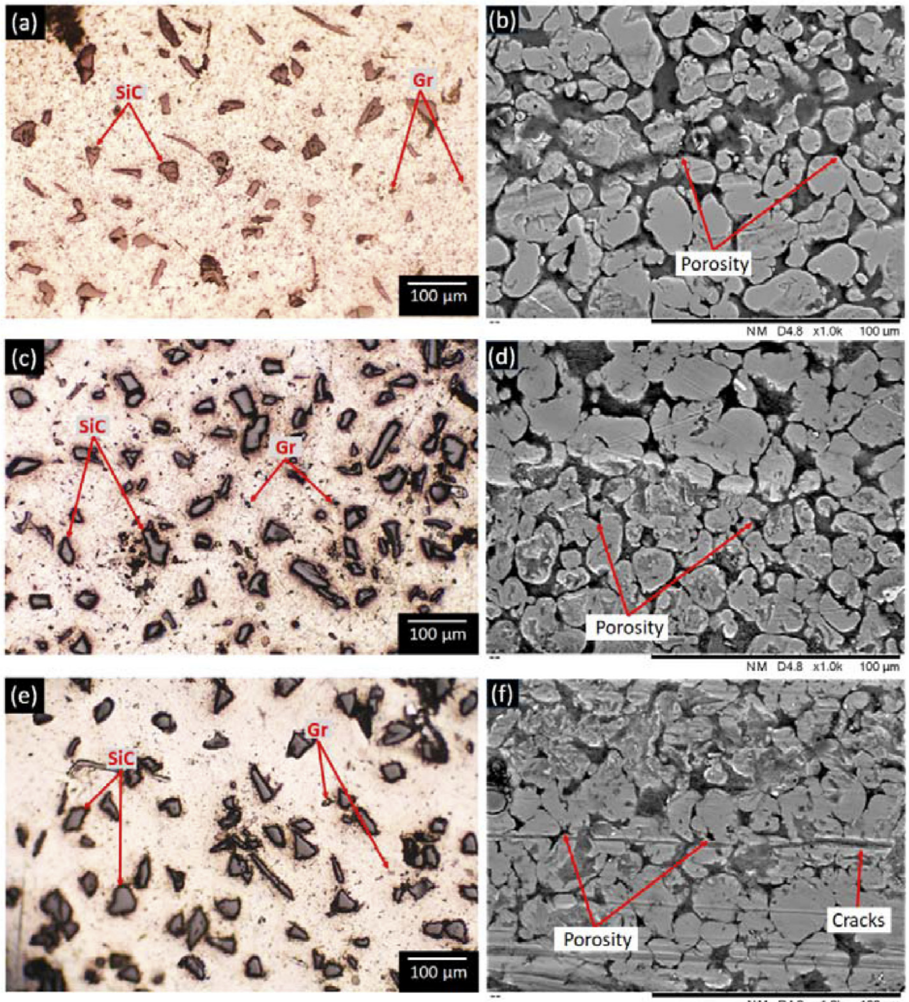

Fig. 5. Optical and SEM micrographs of hybrid MMC (a) (b) Mg+5%Gr+10%SiC, (c) (d) Mg+5%Gr+15%SiC and (e) (f) Mg+5%Gr+20%SiC.

Table 2
Mechanical properties of pure Mg, Mg+5%Gr and hybrid MMCs with different wt% of SiC.

Sample	Vickers microhardness (HV)	Tensile strength (MPa)	% of elongation	Flexural strength (MPa)
S1	34	126	8.4	142
S2	26	115	6.7	131
S3	43	137.7	4.1	151
S4	51	149	2.3	169
S5	62	158.6	1.9	177

Moreover, the hybrid composite samples S3 (Mg+5%Gr+10%SiC) and S4 (Mg+5%Gr+15%SiC) display around 20% and 30% greater tensile strength, respectively, compared to the Mg+5%Gr composite, and 9% and 18% tensile strength increment, respectively, as referred to the pure Mg base material. Therefore, it is very obvious that the inclusion of SiC particles in the Mg+5%Gr composite enhances the ultimate tensile strength. This is because SiC and Gr reinforcement particles are very compatible and develop good bonding with pure Mg and also with each other, which results in withstanding more load as compared to pure Mg. Fig. 7 represents the tensile fracture surface of the pure Mg and the three hybrid MMC samples. A significant number of voids are observed in the pure Mg, indicating ductile fracture. Besides, voids and SiC particle debonding are observed in all the hybrid MMC materials, indicating mixed-mode fracture in hybrid MMCs. Among the three hybrid MMCs, sample S5 (Mg+5%Gr+20%SiC) demonstrates fewer voids but more particle debonding.

The presence of a large quantity of the reinforcement particles in this MMC reduces the ductility and causes a considerable number of particles becoming debonded during tensile loading that indicates the brittle fracture. In order to check the ductility of the hybrid MMCs, the percentage of elongation of all the fabricated samples was calculated and the results are presented in Table 2. It is evident from the result that the elongation percentage decreases with the increasing number of SiC particles in the hybrid MMCs indicating the reduction of ductility in the hybrid MMC materials. Due to the inclusion of SiC particles, a considerable portion of a hard ceramic phase is present in the hybrid MMCs that is responsible for the localized crack initiation and increases the embrittlement effect in the composite due to local stress concentration at the

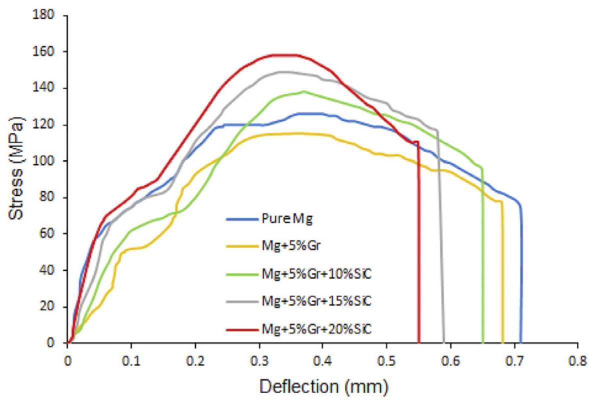

Fig. 6. Stress–strain diagram of pure Mg, Mg+5%Gr and hybrid MMCs with different wt% of SiC.

3.3. Wear behavior

The wear behavior of all the fabricated samples was tested at room temperature with varying loads and sliding speeds by using a pin-on-disc tribometer and the values of the wear rates are presented in Table 3. Moreover, the wear rate results are presented in a graph as a function of load and sliding speed and shown in Fig. 8. The graph in Fig. 8(a) shows that the wear rate is proportional to the applied load. The sample S2 (Mg+5%Gr) displays a specific wear rate of 0.00087 mm^3/N-m at 10 N load and this value increases to 0.0023 mm^3/N-m once the load extends to 30 N. In addition, the wear rates of 0.0026 mm^3/N-m and 0.0031 mm^3/N-m are measured in the hybrid composite samples S4 (Mg+5%Gr+15%SiC) and S5 (Mg+5%Gr+20%SiC), respectively, at the load of 10 N whereas these two hybrid MMCs show a higher value of wear rate of 0.0055 mm^3/N-m and 0.0067 mm^3/N-m, respectively, at 30 N load. These two hybrid MMCs which contain a higher percentage of the SiC reinforcement exhibit higher wear rates in comparison to the composites having no SiC particles (Sample S2). This increasing trend of the wear rate in the hybrid MMCs is due to the presence of a higher concentration of hard SiC particles which develop inconsistent elastic–plastic interaction between the reinforcement and the matrix and thus enhances the possibility of growing cracks in the hybrid MMC material, and increases the abrasion wear. In contrary, the hybrid MMC sample S3 which contains Mg+5% Gr+10%SiC exhibits the lowest wear rate at all the applied loads.

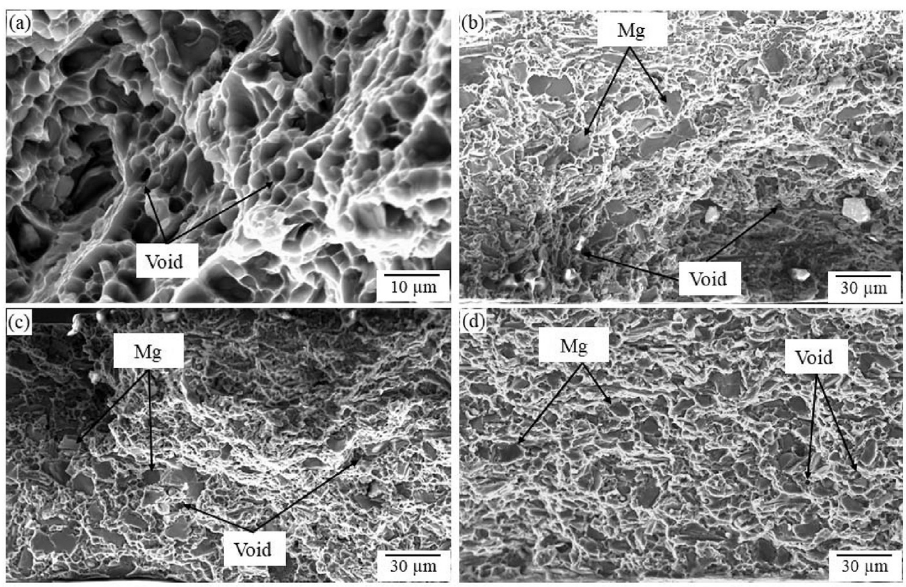

Fig. 7. SEM micrographs of tensile fracture surface (a) Pure Mg, (b) Mg+5%Gr+10%SiC, (c) Mg+5%Gr+15%SiC and (d) Mg+5%Gr+20%SiC.

interface of the reinforcement and the matrix material. The flexural strength of all the fabricated samples was measured by using the conventional three-point bending test and the results are also presented in Table 2. It is observed that the flexural strength of sample S2 (Mg+5%Gr) is the lowest and this value increases once SiC particles are added to the composite. Besides, the flexural strength rises proportionally with the volume of SiC particles in the composite. Therefore, it is well understood that the hybrid MMC sample S5 which is composed of 20% SiC (Mg+5%Gr+20%SiC) displays the highest flexural strength. This composite exhibits around 35% increment of the flexural strength as compared to the Mg+5% Gr and 24% increment of the flexural strength of the pure magnesium. Besides, the other two hybrid MMC samples which were fabricated with 10% SiC and 15% SiC show around 15% and 29% increase of the flexural strength, respectively, as compared to Mg-5%Gr MMC and 6% and 19% increment of the flexural strength, respectively, of the pure magnesium. This flexural strength increment in the hybrid MMCs occurred due to the addition of hard SiC particles which create good bonding with the Mg matrix and graphite and therefore achieve a high level in withstanding high loads compared to pure Mg.

Table 3
Result of specific wear rate at different load and sliding speed.

Load (N)	Sliding Speed (m/s)	Specific wear rate (mm^3/N-m)				
		S1	S2	S3	S4	S5
10	0.5	0.0085	0.00087	0.00064	0.0026	0.0031
20	0.5	0.012	0.0012	0.00084	0.0047	0.0056
30	0.5	0.017	0.0023	0.0019	0.0055	0.0067
10	0.5	0.0082	0.00091	0.00076	0.0021	0.0036
10	0.8	0.0092	0.0011	0.00097	0.0035	0.0042
10	1.0	0.011	0.0014	0.001	0.0041	0.0048

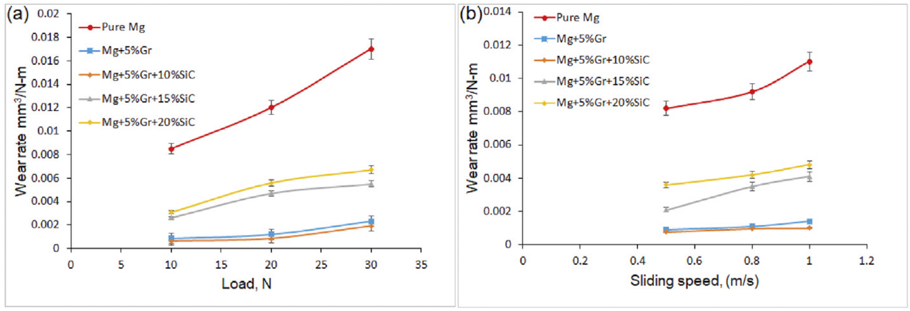

Fig. 8. (a) Variation of the wear rate with the varying applied load, (b) Variation of the wear rate with the varying sliding speed.

This hybrid MMC displays a 92% lower wear rate in comparison to the pure magnesium and a 26% lower wear rate than the Mg+5%Gr MMC. The similar tendency of the wear rate is also observed in Fig. 8(b), where the wear rate was measured in relation to the sliding speed. In this case also the sample S3 which is composed of 5% Gr and 10% SiC (Mg+5%Gr+10%SiC) shows the lowest specific wear rate as compared to other compositions. The graphite particles present in the composite act as a lubricant and develop a thin lubricating film on the tribosurface which prevents the metal to metal contact.

In addition, the SiC particles act as the load-bearing elements in the hybrid MMCs and help to form a more stable lubricating film on the tribo-surface of the hybrid composites. The cumulative effect of 5% graphite and 10% SiC particles form a more resistant tribolayer on the contact surface, thus decrease the wear rate. Besides, the coefficient of friction of the pure Mg, Mg+5%Gr and the hybrid MMCs with varying SiC content are depicted in Fig. 9. The results illustrate that the coefficient of friction in the hybrid MMC increases as the percentage of the SiC particles increases in the MMC. The coefficient of friction of the samples S4 and S5 is quite high as compared to that of Mg+5%Gr composite. The high inclusion of SiC particles in these two hybrid MMCs increases the hard phase and brittleness resulting in producing high porosity and cracks in the composite surface. This eventually affects the wear properties and increases the frictional coefficient in MMCs. Conversely, it can be seen in the figure that the lowest coefficient of friction obtained in the hybrid MMC sample S3 (Mg+5%Gr+10%SiC) is 0.24. This frictional coefficient value is 53% and 20% lower than that of the pure magnesium and Mg+5%Gr composite, respectively. The graphite reinforcement particles form a smeared film over the contact surface which acts as a solid lubricant and the SiC particles strengthen and stable the tribosurface. Therefore, the combination of 5% graphite and 10% SiC particles forms a stable tribosurface and eventually produces the lowest frictional coefficient in this MMC. To further investigate the wear mechanism in the hybrid MMC, the worn surfaces of the MMCs were examined by SEM and the results are presented in Fig. 10. The morphology of the worn surfaces indicates the existence of the abrasion and delamination wear mechanisms in these hybrid MMCs. Large grooves can be seen along the sliding direction in all the MMCs indicating the plastic deformation which occurs due to the abrasion. Debris is also found in many places indicating the delamination mechanism. Besides, pores and cracks are observed in many places in the hybrid MMC samples S4 and S5 which are composed of 15% and 20% SiC particles, respectively. The existence of a large number of pores in the tribosurface of the hybrid MMC clearly indicates the surface deterioration which occurs due to the severe plastic deformation. The presence of a higher percentage of hard ceramic SiC particle reinforcement in these two hybrid composites results a high plastic deformation and deteriorates the surface condition. Therefore, the wear rate and the friction coefficient increase in these MMCs. Conversely, in the worn surface of sample S3 (Fig. 10 a,b) which is composed of 5% Gr and 10% SiC particles, pores and cracks are not noticed. Debris which is formed on the surface is also relatively low as compared to sample S4 and S5. Besides, a smooth graphite lubricating layer is observed in the worn surface of sample S3

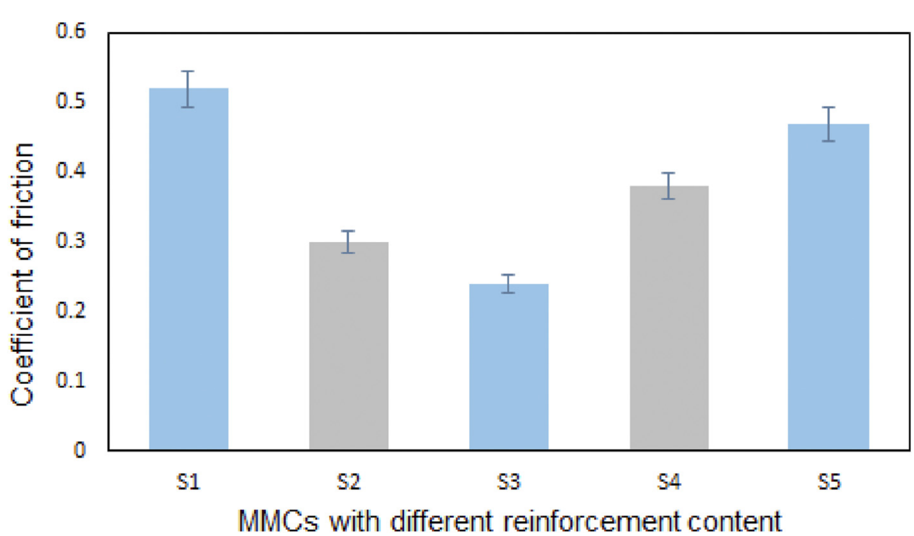

Fig. 9. Coefficient of friction with varying reinforcement content.

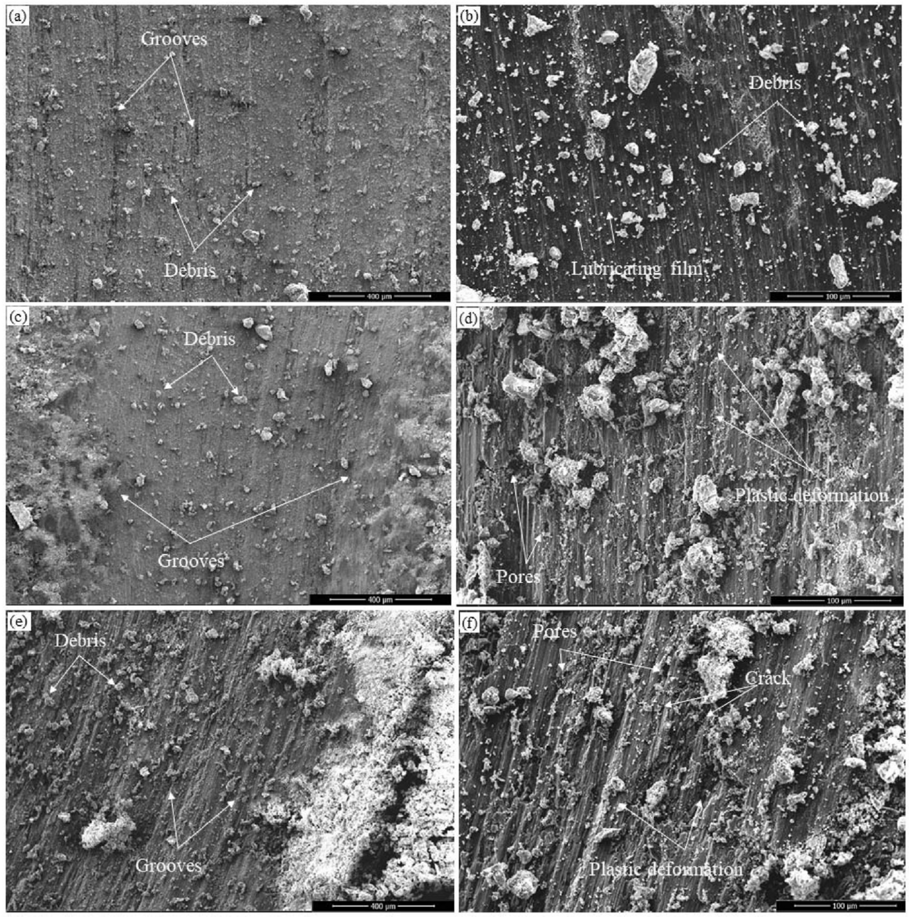

Fig. 10. SEM micrographs of the worn surface of (a) (b) Mg+5%Gr+10%SiC, (c) (d) Mg+5%Gr+15%SiC and (e) (f) Mg+5%Gr+20%SiC.

which uniformly covers the entire worn surface of the hybrid MMC (Fig. 10(b)). The smeared graphite particles form a thin rich graphite tribofilm between the sliding surfaces and prevent the direct contact between the pin and disc surfaces. This tribofilm minimizes the degree of shear stress transferred to the sliding material underneath the sliding contact area which results in less plastic deformation in the subsurface region. The collective effect of 5% Gr and 10% SiC particles form a more resistant and stable tribolayer. The graphite film works as a protective layer and prevents the breaking of hard SiC particles resulting in less surface damage. Therefore, the wear rate and the friction coefficient are reduced in this hybrid MMC and the overall wear performance is improved in comparison to the base material and Mg-Gr composite. Hence, from the above results, it can be concluded that the addition of graphite to the base material significantly improves the wear behavior of the composite and the collective effect of 5% Gr and 10% SiC particles forms a more resistant and stable tribolayer. Thus, the hybrid MMC composed of Mg+5%Gr+10%SiC exhibits superior wear properties.

4. Conclusion

The mechanical and wear behaviors of the self-lubricating hybrid MMCs were investigated in this research. A tremendous enhancement of the hardness in the range of 65–138% and of the tensile strength in the range of 20–38% was observed in the hybrid MMCs depending on the volume of the SiC particles. The tribological properties including the wear rate and coefficient of friction are also remarkably improved. This improvement of the mechanical and tribological properties in the hybrid MMCs are attributed to the combined effect of the SiC and graphite reinforcement particles. The SiC particles strengthen the composite while the graphite works as a protective layer and prevents the breaking of the hard SiC particles. Therefore, the hybrid MMCs possess the superior strength and wear resistance. Among the three compositions of the hybrid MMCs sample S3 composed of Mg+5% Gr+10%SiC exhibits a tensile strength of 137.7 MPa which is 9% greater than that of the monolithic Mg. Besides, this material shows an around 92% lower wear rate and 53% lower friction coefficient than the matrix Mg. The cumulative effect of 5% Gr and 10% SiC particles helps strengthen the mechanical properties as well as form a more resistant and stable tribolayer as compared to other materials. Therefore, this composition (Mg+5%Gr+10%SiC) of hybrid MMC can be considered as the optimum value to get the best mechanical and tribological properties and this hybrid MMC can be considered as a potential material for developing components involved in the tribological operations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The financial support provided under the project Fundamental Research Grant Scheme (FRGS Ref: FRGS/1/2018/TK03/UMP/02/14) has been gratefully acknowledged.

References

[1] B.L. Mordike, T. Ebert, Magnesium: properties - applications – potential, Mater. Sci. Eng A. 302 (2001) 37–45.
[2] I. Aatthisugan, A. Razal, D. Rose, J. Selwyn, Mechanical and wear behaviour of AZ91D magnesium matrix hybrid composite reinforced with boron carbide and graphite, J. Magnes. Alloys. 5 (2017) 20–25.
[3] S. Aravindan, P.V. Rao, K. Ponappa, Evaluation of physical and mechanical properties of AZ91D/SiC composites by two step stir casting process, J. Magnes. Alloys. 3 (1) (2015) 52–62.
[4] J. Satish, K.G. Satish, Preparation of magnesium metal matrix composites by powder metallurgy process, IOP Conf. Ser. Mater. Sci. Eng. 310 (1) (2018).
[5] P. Narayanasamy, N. Selvakumar, Tensile, compressive and wear behaviour of self-lubricating sintered magnesium based composites, Trans. Nonferrous Metals Soc. China 27 (2017) 312–323.
[6] C. Bin, Y. Tan, Y. Tu, X. Wang, H. Tan, Tribological properties of Ni-base alloy composite coating modified by both graphite and TiC particles, Trans. Nonferrous Metals Soc. China 21 (2011) 2426–2432.
[7] S. Basavarajappa, G. Chandramohan, A. Mahadevan, M. Thangavelu, R. Subramanian, P. Gopalakrishnan, Influence of sliding speed on the dry sliding wear behaviour and the subsurface deformation on hybrid metal matrix composite, Wear 262 (2007) 1007–1012.
[8] J.B. Yang, C.B. Lin, T.C. Wang, H.Y. Chu, The tribological characteristics of A356.2Al alloy/Gr(p) composites, Wear 257 (2004) 941–952.
[9] R. Deaquino-Lara, N. Soltani, A. Bahrami, E. Gutiérrez-Castañeda, E. García-Sánchez, M. Hernandez-Rodríguez, Tribological characterization of Al7075-graphite composites fabricated by mechanical alloying and hot extrusion, Mater. Des. 67 (2015) 224–231.
[10] T. Lokesh, U.S. Mallik, Dry sliding wear behaviour of Al/Gr/SiC hybrid metal matrix composites by Taguchi techniques, Mater. Today: Proceedings 4 (2017) 11175–11180.
[11] N. Zamani, A.A. Iqbal, D. Nuruzzaman, Mechanical and tribological behavior of powder metallurgy processed aluminum–graphite composite, Russ. J. Non-Ferrous Metals 60 (2019) 274–281.
[12] A. Al-maamari, A.A. Iqbal, D. Nuruzzaman, Wear and mechanical characterization of Mg–Gr self-lubricating composite fabricated by mechanical alloying, J. Magnes. alloys. 7 (2019) 283–290.
[13] F. Akhlaghi, B. Zare, A. idaki, Influence of graphite content on the dry sliding and oil impregnated sliding wear behaviour of Al2024–graphite composites produced by in-situ powder metallurgy method, Wear 266 (2009) 37–45.
[14] L. Zhang, Q. Wang, W. Liao, W. Guo, W. Li, H. Jiang, W. Ding, Microstructure and mechanical properties of the carbon nanotubes reinforced AZ91D magnesium matrix composites processed by cyclic extrusion and compression, Mater. Sci. Eng. 689 (2017) 427–434.
[15] K. Shyam, R. Bauri, D. Yadav, Wear properties of 5083Al–W surface composite fabricated by friction stir processing, Tribol. Int. 101 (2016) 284–290.
[16] P. Ravindran, K. Manisekar, P. Narayanasamy, P. Rathika, Tribological properties of powder metallurgy-processed aluminium self-lubricating hybrid composites with SiC additions, Mater. Des. 45 (2013) 561–570.
[17] G. Wan-li, Bulk Al/SiC nanocomposite prepared by ball milling and hot pressing method, Trans. Nonferrous Metals Soc. China 16 (2006) 398–401.
[18] F. Akhlaghi, A. Lajevardi, H.M. Maghanaki, Effects of casting temperature on the microstructure and wear resistance of compocast A356/SiCp composites: a comparison between SS and SL routes, J. Mater. Process. Technol. 155 (2004) 1874–1880.
[19] S. Mula, P. Padhi, S.C. Panigrahi, S.K. Pabi, S. Ghosh, On structure and mechanical properties of ultrasonically cast Al–2% Al_2O_3 nanocomposite, Mater. Res. Bull. 44 (2009) 1154–1160.
[20] S.N. Prabhakar, N. Radhika, R. Raghu, Analysis of tribological behavior of aluminum/B_4C composites under dry sliding motion, Procedia Eng. 97 (2014) 994–1003.