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Effect of Sliding Velocity on Wear Behavior of Magnesium Composite Reinforced with SiC and MWCNT

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Abstract

This paper investigates the tribological characteristics of magnesium (Mg) composites prepared by powder metallurgy route. Attempt was made to identify the effect of filler types (i.e. micro-sized silicon carbide (SiC) particles and multi-walled carbon nanotube (MWCNT)) on Vickers hardness, specific wear rate and coefficient of friction of magnesium composite. Experiment was conducted under dry sliding condition using a pin-on-disc configuration against a grey cast iron counterbody at a constant load of 40 N with different sliding velocities (0.5, 1.5 and 3.5 m/s) at sliding distance of 5000 m. Throughout this work, hardness value increased with the addition of SiC and MWCNT. The coefficient of friction and specific wear rate varied with the sliding velocities, hence indicating that different wear mechanisms are taking place at different sliding velocities. The coefficient of friction at the highest sliding velocity of 3.5m/s was independent of filler types. However, the incorporation of MWCNT minimized the specific wear rate of the composite at sliding velocity of 3.5m/s.

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Keywords: Magnesium, Silicon Carbide, Carbon Nanotubes, Powder Metallurgy, Wear Properties.

1. Introduction

Currently, with the concurrent interest in requirements of high tribological resistance and weight reduction, the research activity of magnesium (Mg) based metal matrix composites (MMCs) have induced significantly contribution in automotive industry [1-7]. One of the early studies reveals that the wear rates of Mg-AZ91 alloy composite decrease with increasing feldspar particle content [1]. Thakur and Dhindaw [2] reported that well-dispersed SiC particles can contribute to better wear resistance, coefficient of friction and microhardness in aluminum (Al) and Mg metals. Similar beneficial effect was also found by Lim et al. [3] when they incorportated SiC in Mg-AZ91 alloy. To further improve tribology behavior, incorporation of nano fillers into pure Mg has been demonstrated to improve wear resistance [4, 5]. Mondal and Kumar [6] observed that the wear rate of Mg-AE42 alloy hybrid composites reinforced with Saffil short fibers and SiC particles exhibit a lower wear rate than the Saffil short fibers reinforced composite and unreinforced alloy at all loads. Oneida et al. [7] also showed that the reinforcing carbon nanotubes (CNTs) and silica (SiO_2) improved the wear resistance and lower the coefficient of friction of hybrid composites since no adhesion and stick-slip phenomenon occurred.

The primary aim of this paper is to investigate the tribological behaviour of magnesium under the effect of

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filler types (i.e. micro-sized silicon carbide (SiC) particles and multi-walled carbon nanotubes (MWCNTs)) by a pin on disc test under a constant load of 40 N with different sliding velocities (0.5, 1.5 and 3.5 m/s) for sliding distance of 5000 m.

2. Experimental Details

2.1. Raw Materials

The primary material, magnesium (Mg) with (> 97%) purity purchased from Merck Schuchardt, Germany was used as the matrix material. Two different types of reinforcement namely silicon carbide (SiC) and multi-walled carbon nanotubes (MWCNTs) were employed. SiC powders with an average particle size within the range of 20-40 μm was obtained from Sigma- Aldrich, Malaysia while the 88% purity industrial grade MWCNTs with an outer diameters ranging from 20-40 nm and length ranging from 10-30 μm was acquired from Nanostructured & Amorphous Materials, Inc.

2.2. Fabrication of Magnesium Composite

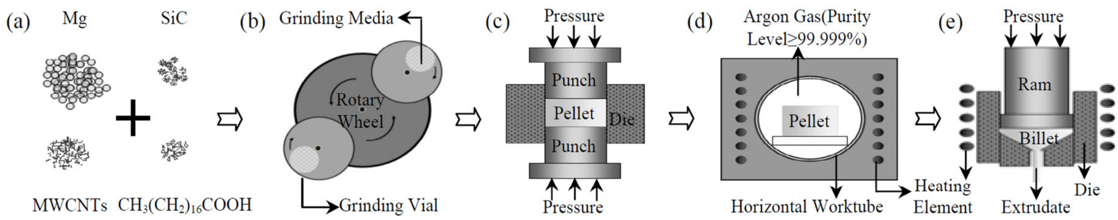

Fig. 1. Schematic diagram of hybrid composite fabrication process in sequence (a) raw material (b) mechanical mixing (c) compaction (d) sintering and (e) hot extrusion.

The powder metallurgy route as shown in Fig.1 was adopted to produce cylindrical samples for pin-on-disc wear test. Initially, the as-received powders were weighed in accordance to different compositions as stated in Table 1. The appropriate proportions were then mixed by using Insmart planetary mill at 200 rpm for total 2 hours with an interruption of 30 minutes after an hour. 1% of stearic acid was added as a process control agent to reduce the possibility of MWCNTs entanglement and the effect of excessive cold welding. Upon mixing, the powder mixtures were uniaxially cold compacted under a compaction speed of 1 mm/min until reaching a pressure of 103 MPa. Subsequently, the green compacts were sintered presureless in a horizontal tube furnace with continuous supply of argon gas (purity level ⩾ 99.999%) at a flow rate of 1 l/min. The sintering operation was carried out by heating the furnace at a rate 10˚C /min until it reached to 550 ºC where the sintered samples were soaked for 2 hours. Thereafter, the sintered pellets hot extruded at an extrusion ratio of 16:1 using a 150 ton hydraulic press machine. Prior to extrusion, the sintered pellet were placed in extrusion die filled with graphite and preheat at 400 ± 10 ºC for 1 hour. Extrusion was carried out at 380 ± 10ºC with a ram speed of 0.1 mm/s. Upon extrusion, extrudates were sectioned and the surface was polished to a surface roughness of Ra 0.4.

Table 1. Description of composition and abbreviated nomenclature of the samples

Abbreviated Nomenclature	Composition (wt.%)		
	Mg	SiC	MWCNTs
Mg	100	0	0
Mg/SiC	90	10	0
Mg/SiC/MWCNT	89	10	1

2.3. Microhardness Measurements

Vickers microhardness test was carried out on the polished surfaces of extruded specimens by using pyramidal shape diamond indenter with a facing angle of 136˚ under load of 10 g with dwell time of 15s according to ASTM E384–99.

2.4. Wear Test

Dry sliding tests were conducted using Ducom pin-on-disc tester according to ASTM G99-05. Pin specimens machined from the as-extruded rods of diameter 10 mm and length of 25 mm were worn against an grey cast iron (Grade 4E) counterbody with a bulk hardness of 82 ± 1 HRB. Before the commencement of each wear test, the pins and counterbody surfaces were degreased by acetone and dried to remove surface contaminants. All tests were performed at ambient temperature (24 ºC) and relative humidity (52-65%) under applied normal load of 40N with three different sliding velocities 0.5, 1.5 and 3.5m/s corresponding to travelling distance of 5km. Three samples were tested for each test condition and temperature change of the pin throughout the test was measured using chromel-alumel thermocouple contacting very close to the tip of the pin (Fig. 2).The worn pin surfaces and collected wear debris were then examined using Scanning Electron Microscope (SEM) equipped with an energy dispersive X-ray spectroscopy (EDX) to characterize wear surface morphology

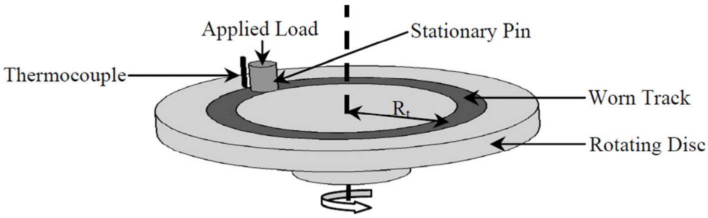

Fig. 2. Schematic configuration of pin-on-disc machine employed for wear test.

3. Results and Discussion

Table 2. Vickers hardness number (HV) measured for different samples

Abbreviated Nomenclature	Vickers hardness number (HV)
Mg	48.3 ± 0.9
Mg/SiC	63.7 ± 1.7
Mg/SiC/MWCNT	68.8 ± 1.7

Table 2 shows the variation of microhardness of monolithic Mg along with its composites. As expected, the Vickers hardness number increases with the addition of SiC and MWCNT. This elevation may contribute from restraining effect of reinforcements (SiC and MWCNT) which constraint the localized matrix deformation during indentation.

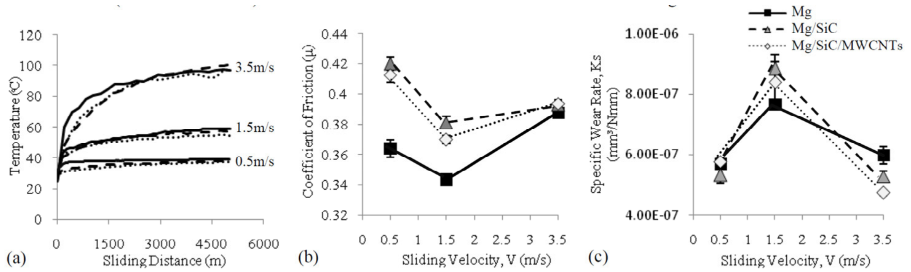

Fig. 3. Variation of (a) temperature (b) mean coefficient of friction [μ], (c) mean specific wear rate Ws [mm^3/Nmm] of different samples at various sliding velocity.

Fig 3a displays contact surface temperature versus sliding distance for different sliding velocities. The interface temperature rises for all materials as time elapsed. High interface temperature in the range of 97-100 ºC was reached at the sliding velocity of 3.5 m/s due to low heat dissipation as compared to high heat generation. However, thermal equilibrium was established between the contact surfaces as time elapsed and resulted in the approximately constant temperature.

Fig. 3b shows the changes of coefficient of friction where it decreases from sliding velocity of 0.5 m/s to 1.5 m/s and increases at sliding velocity of 3.5 m/s. The above results indicate that different wear mechanisms are taking place at different sliding velocities. For material-wise, there is a small reduction in the coefficient of friction for Mg/SiC/MWCNTs composite as compared to Mg/SiC particularly at low sliding velocities of 0.5 and 1.5m/s respectively. These can be explained by the self- lubrication and bearing effect induced by the network structured nanotubes dispersed in the Mg matrix [7]. The adhesion effect of wear at sliding velocity of 3.5 m/s has caused increase in the coefficient of friction from sliding velocity 1.5 m/s to 3.5 m/s for all materials irrespective of SiC and MWCNTs addition.

Fig 3c illustrates the changes in specific wear rates for the Mg and its composites for different sliding velocities. Irrespective of material types, it is noted that specific wear rates are maximum at the sliding velocity of 1.5 m/s. The addition of SiC and MWCNT actually increases specific wear rates at sliding velocity of 1.5 m/s. At the highest velocity of 3.5 m/s, the addition of SiC and MWCNT improve the wear resistance but at the lowest velocity of 0.5 m/s the specific wear rates are almost equal for all types of samples.

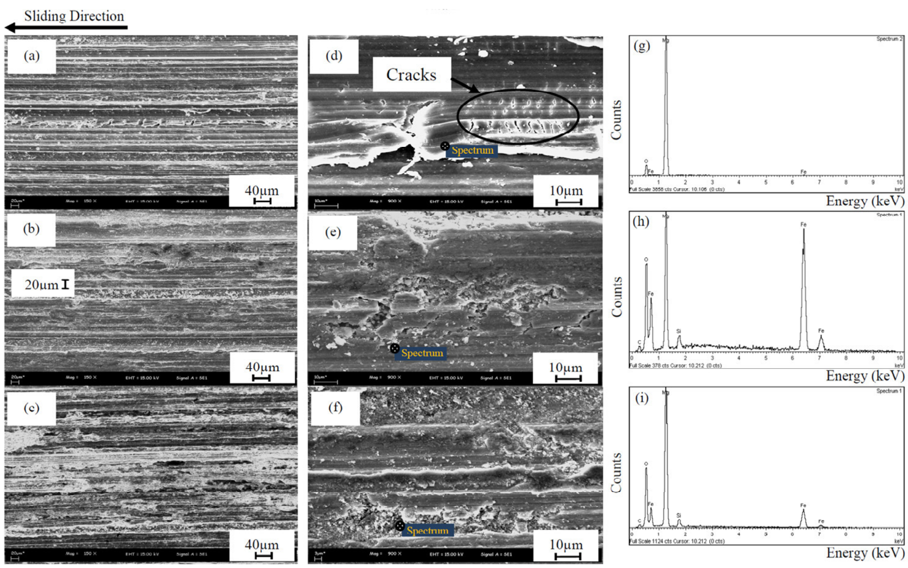

Fig. 4. SEM images of worn surface (a) Mg, (b) Mg/SiC, (c) Mg/SiC/MWCNTs at 150 × magnification, (d) Mg, (e) Mg/SiC, (f) Mg/SiC/MWCNTs at 900 × magnification, Energy dispersive X-ray (EDX) spectra (g) from Fig. d , (h) from Fig. e (i) from Fig. f under load of 40 N and sliding velocity of 0.5m/s

SEM examinations (Fig.4) show numerous continuous grooves parallel to the sliding direction at the sliding velocity of 0.5m/s. These parallel grooves are the evidence of abrasion which usually caused by the presence of hard particles between the pin and disc that cut into the wear surface. It is also observed that there is an evidence of cracks which are perpendicular to the sliding direction (Fig.4d) and fragmentation (Fig.4e and f). The corresponding EDXs (Fig.4g-i) show the presence of oxygen in addition to iron and magnesium peak. The relative motion between pins and disc surface generates frictional heat which causes oxidation of the wear surface. However, based on the appearance of the worn surfaces, there is no major difference between the extents of abrasion for all specimens. Hence, the changes in wear rates are insignificant.

As velocity increases from 0.5 m/s to 1.5 m/s, the wear rate increases for all materials. Similarly, abrasion took place causing material removed on the abrasion groove. The width of the grooves increases approximately from 20μm (Fig.4b) to 30μm (Fig.5b) which indicates a higher degree of material removal by cutting action. At high magnification (Fig.5d-f), severe detachment of sheet-like delaminated wear debris leaving behind shallow craters is observed for all materials. Oxidation of wear surface also took place as the EDX Spectra (Fig.5g-i) confirmed the presence of oxygen peak. In comparison, damages in terms of delamination areas are larger for Mg/SiC than Mg and Mg/SiC/MWCNTs, hence Mg/SiC contributed the highest specific wear rate under sliding velocity of 1.5m/s.

As velocity increases from 1.5 m/s to 3.5 m/s, the wear rate decreases for all materials. The well-defined grooves observed at the lower velocities have gradually transformed to shallow scratches accompanied by plastic deformation as the sliding velocity increases to 3.5 m/s (Fig. 6a-c). This can be correlated to the contact surface temperature (Fig 3a) whereby the softening effect of magnesium is prevalent due to the higher rate of frictional heat generated as the sliding velocity increases. In fact, earlier researchers have found similar effects attributed to tendency of plastic deformation with higher velocity [3, 4-6]. Consequently it leads to transition from cutting to ploughing action where the material is displaced on either side of the abrasion groove without being removed [4]. Therefore, it might be reasonable to explain the reduction in wear rates as sliding velocity increases from 1.5 to 3.5 m/s. In comparison of materials, the presence of SiC and hybrid SiC/MWCNTs appears to be marginally beneficial at high sliding velocity of 3.5 m/s, decreasing wear rates by 10 and 21.1% as compared to Mg respectively (Fig 3c). Indications of rows of furrows at high magnification (Fig. 6d-f) are characteristics of adhesion in which the higher rictional sliding velocity softens the pin surface and hence increases sticking tendency between the pin and counter surfaces. In addition, lesser counts of oxygen peak from the EDX analysis (Fig. 6g-i) may indicate that the rate of removal of the oxide film through sliding is greater than its rate of formation. However, a

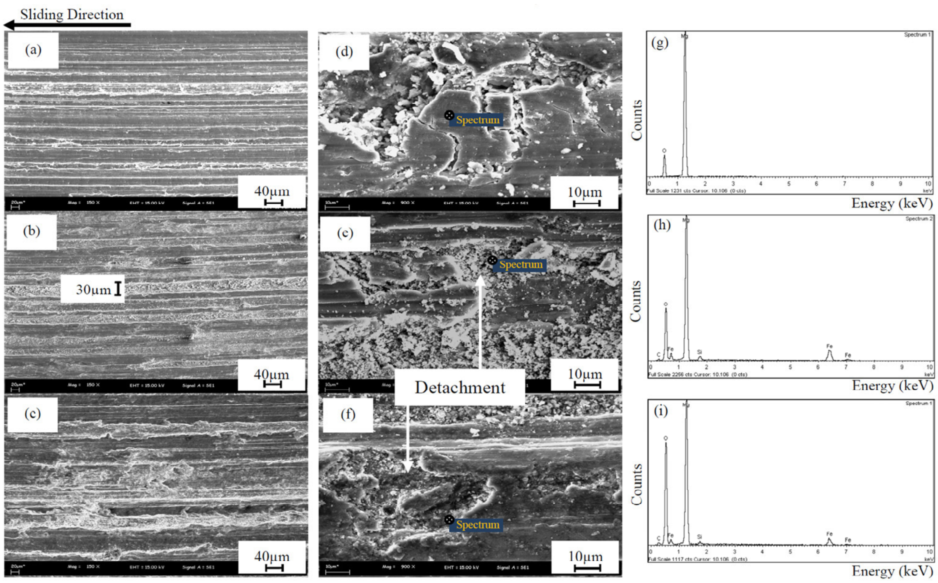

Fig. 5. SEM images of worn surface (a) Mg, (b) Mg/SiC, (c) Mg/SiC/MWCNTs at 150 × magnification, (d) Mg, (e) Mg/SiC, (f) Mg/SiC/MWCNTs at 900 × magnification, Energy dispersive X-ray (EDX) spectra (g) from Fig. d , (h) from Fig. e (i) from Fig. f under load of 40 N and sliding velocity of 1.5m/s.

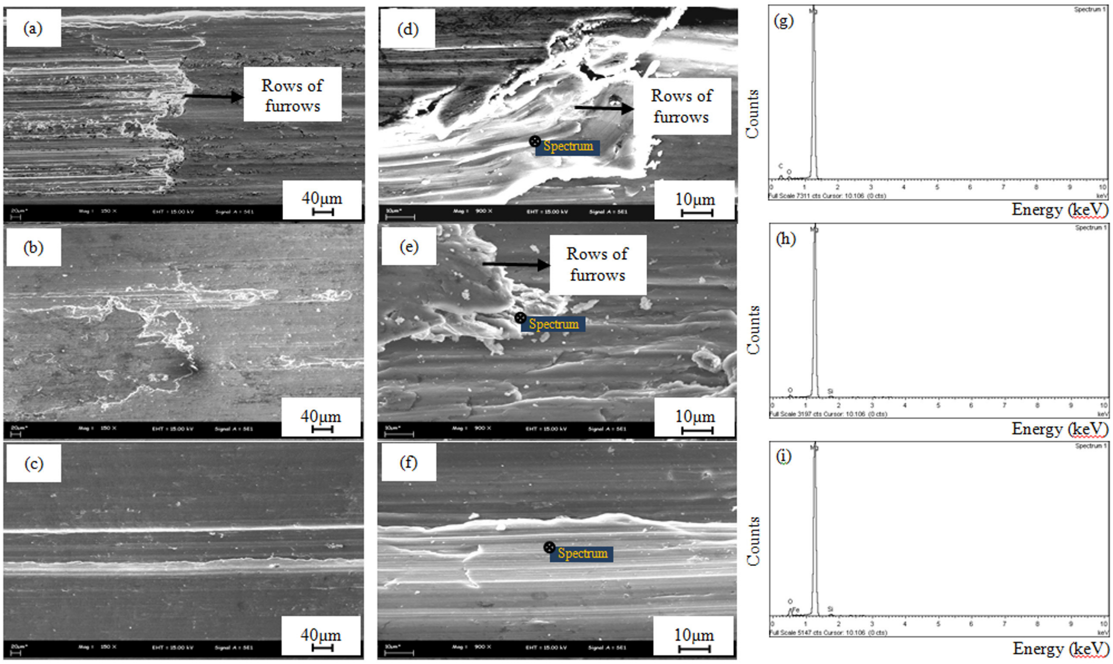

Fig. 6. SEM images of worn surface (a) Mg, (b) Mg/SiC, (c) Mg/SiC/MWCNTs at 150 × magnification, (d) Mg, (e) Mg/SiC, (f) Mg/SiC/MWCNTs at 900 × magnification, Energy dispersive X-ray (EDX) spectra (g) from Fig. d , (h) from Fig. e (i) from Fig. f under load of 40 N and sliding velocity of 3.5m/s.

similar phenomenon at higher sliding velocity has been observed by the researchers [3, 4] where composites (Fig.6e and f) show the less adhesion area than the unreinforced magnesium (Fig.6d). This may be attributed to the incorporation of thermally stable and high modulus MWCNTs and SiC particles that increases the intrinsic hardness of composite and resist the material flow during sliding [6]. Especially MWCNTs played an important role at higher sliding velocity (3.5 m/s) to form the lubricating condition at the sliding interface between the extruded magnesium and the counterbody due to their network structure on the sliding surface and produce better wearing resistance at high velocity. Hence, the extent of plastic deformation of matrix is lesser in the case of Mg/SiC and Mg/SiC/MWCNTs composites.

The examination of the wear debris reveals the presence of small fragments and ribbon-like strips materials (Fig. 7) due to abrasion. In fact, the occurrence of magnesium ribbon-like strips can be detected for Mg specimens at all velocities. On the other hand, the presence of fine oxide debris (Fig. 8) confirming that oxidation of the wear surface took place from the frictional heat generated by the sliding motion between pins and disc surface. Besides that, the flakes or sheets like wear debris (Fig. 9) collected from Mg under sliding velocity of 1.5m/s indicates that delamination was one of the predominant wear mechanisms and hence produced greater wear.

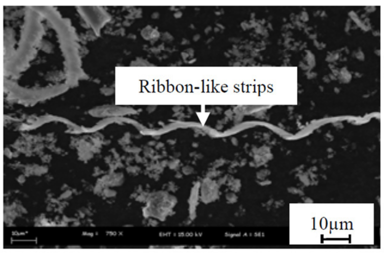

Fig. 7. Magnesium ribbon-like strips debris collected from Mg under sliding velocity of 0.5m/s at 1500 × magnification.

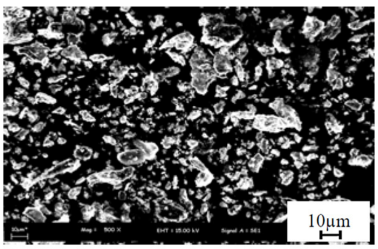

Fig. 8. Fine oxide wear debris collected from Mg/SiC/MWCNTs under sliding velocity of 1.5m/s at 500 × magnification.

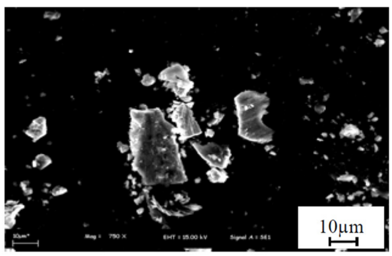

Fig. 9. Flake- or sheet-like wear debris collected from Mg under sliding velocity of 1.5m/s at 750 × magnification.

4. Conclusion

Tribological behavior of monolithic Mg, composites Mg/SiC and Mg/SiC/MWCNTs developed by powder metallurgy route were investigated under dry sliding condition using a pin-on-disc configuration against a grey cast iron counterbody under a constant load of 40 N with different sliding velocities of 0.5, 1.5 and 3.5 m/s at sliding distance of 5000 m. The results obtained indicate that the incorporation of SiC and MWCNTs reinforcement improved the Vickers hardness. The wear resistances of the hybrid composite were higher in comparison with the monolithic Mg and Mg/SiC under the combination of high load of 40 N and 3.5 m/s, but did not improve wear resistance under low sliding velocity of 0.5 and 1.5 m/s. Abrasion and delamination were the dominant wear mechanisms at sliding velocity of 0.5 and 1.5 m/s while adhesion occured only under the highest sliding velocity of 3.5m/s.

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