Wear properties of magnesium matrix composites reinforced with SiO_2 particles

Mustafa Aydin
Department of Mechanical Engineering, Dumlupinar University, Kütahya, Turkey, and

Fehim Findik
Department of Materials Technology, Sakarya University, Adapazarı, Turkey

Abstract

Purpose – The purpose of this paper is to improve the wear resistance and tribological properties of magnesium and its alloys in order to apply them to the friction components.

Design/methodology/approach – Wear test, microhardness measurements, X-ray diffraction (XRD), optical and electron microscopy examinations were applied.

Findings – The ceramic SiO_2, which has different particle-sized reinforced pure Mg-SiO_2 composites, is produced by powder metallurgy using high ball milling, pressing and sintering. Mg_2Si and MgO intermetallic phases produced by powder metallurgy in the Mg-SiO_2 composite are dispersed as homogeneous into the Mg matrix. Mg-SiO_2 composites exhibited a lower wear rate than the unreinforced pure magnesium specimens. Despite the pure Mg, the wear resistance of the composite is 61 per cent and the wear volume decrease with reducing SiO_2 particle size. The hardness of the composite is increased in a ratio of 70 per cent with the distribution of the Mg_2Si and MgO phases into the Mg matrix.

Practical implications – In this paper, pure Mg powder with purity of 99.9 per cent and SiO_2 powders with a mean particle size of -500, -250, -125, -75 and $-10\,\mu$m are mixed by mechanical alloying. The wear behaviour of Mg-SiO_2 composite, with the different particle-sized composites dispersed with Mg_2Si and MgO intermetallic phases under dry friction condition is studied. The microstructural and mechanical properties of composite material samples are determined by differential scanning calorimeter, XRD, microhardness, optical and scanning electron microscopy tests.

Originality/value – SiO_2 particles distributed in the matrix are effective to improve hardness and wear resistance when contacting counter materials. In the present study, the magnesium powders with different particle size SiO_2 powders are mechanically alloyed with a Turbola Spex 80000 mixer.

Keywords Composite materials, Mechanical behaviour of materials, Wear, Minerals, Alloys

Paper type Research paper

1. Introduction

Magnesium and its alloys, the lightest among structural materials, have become attractive candidates for application in the automotive, aerospace, audio and electronics industries (Mondal *et al.*, 2007; Lu *et al.*, 2003; Mabuchi *et al.*, 1996). These alloys have low wear resistance and hardness, and sticking seizure phenomena easily occur with the counter materials (Kumar *et al.*, 2005). However, magnesium alloys are attractive materials for use in aircraft structures, due to their low density, good casting properties and high specific buckling resistance (Wei *et al.*, 2006; Kondoh *et al.*, 2005). The density of magnesium is about 35 per cent less than that of aluminium and about 77 per cent less than that of steel (Mondal *et al.*, 2007). The development of this high-strength as well as low-density composites resulted in a growing interest in research activities in this field (Sharma *et al.*, 2000). However, a comparative survey revealed that the number of investigations on these materials is not adequate as compared with Al-MMCp (Lu *et al.*, 1998). One of the studies with the tribological behaviour under the sliding condition of Mg and AZ91 alloy with both unreinforced and reinforced with alumina fibres were performed in 1993 (Alahelisten *et al.*, 1993). Afterwards, the sliding wear study on AZ91 alloy reinforced with feldspar particles was conducted by Sharma *et al.* (2000). Their work revealed that the particle-reinforced composite gave better wear resistance than the unreinforced alloy and the wear severity increased with an increase in loads. In other work, Lim *et al.* (2003) have studied the wear behaviour of AZ91 reinforced with SiC particles in a dry sliding wear test. They reported that the addition of the reinforcement was beneficial only at lower loads. In other previous works (Kondoh *et al.*, 2005), magnesium matrix composites with *in situ* formed Mg_2Si dispersoids were developed via the solid state reaction process, when the elemental mixture of magnesium alloy and silicon powder were employed. Mg_2Si has a high hardness of 350-700 HV, a high Young's modulus of 120 GPa and a low density of 1.9 kg/cm^3 (Wang *et al.*, 2007). So far, studies indicated that volume fraction, interparticle distance, particle distribution and particle matrix interface seem to have a strong influence on the mechanical and tribological behaviour of the composite.

In spite of considerable development, the optimization of all these parameters in order to achieve the best service performance is still a major challenge with regard to the wear mechanism under different loading conditions for engine components and the aerospace, audio and electronic industries, it is essential to understand the tribological behaviour of the composites. There is no much study in the literature about the effect of particle size on the wear rate of the Mg-SiO_2 composites. In the present work, the tribological behaviour of Mg-SiO_2 composite with different particle-sized composites

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0036-8792.htm

Industrial Lubrication and Tribology
62/4 (2010) 232–237
© Emerald Group Publishing Limited [ISSN 0036-8792]
[DOI 10.1108/00368791011051099]

dispersed with Mg_2Si and MgO intermetallic phases under dry friction conditions was studied.

2. Experimental procedures

2.1 Materials

Pure Mg powder (mean particle size of 40 μm and purity of 99.9 per cent) and SiO_2 powders with mean particle sizes -500, -250, -125, -75 and -10 μm were mixed by mechanical alloying using a Turbola Spex 80000 machine under an argon atmosphere in the vial cup for a duration of 60 s. The rotational speed of the vial cup was 1,000 rpm. Different-sized SiO_2 powders were used for the formation of Mg_2Si and MgO phases. In order to prevent oxidation, the mixtures were prepared in a glove-box. Then, mixed powders were pressed at 560 MPa and sintered under an argon atmosphere for 45 min at 550°C. The sintering temperature was decided by the differential scanning calorimeter (DSC) because the formation of Mg_2Si phase accompanies exothermic heat.

2.2 Wear test and microhardness

In the wear test of Mg-SiO_2 composites, pin-on-disk type wear test equipment was used for the evaluation of dry tribological properties. Pins of the pure Mg and composites were pressed and sintered to 10 mm in diameter and 15 mm in length. In the wear tests, 4140 carbon steel was used as a counter face with a hardness value of Hardness Rockwell C 58, diameter of 100 mm and width of 30 mm. Sliding speeds of 5, 10 and 20 N loads and 0.5, 1.0 and 2.0 ms^{-1} were used. A fresh disc was used each time and before each test the disc was cleaned with acetone to remove any possible traces of contaminants. The specimens were weighed before and after the test using a balance having an accuracy of $+0.0001$ g. The wear volume was calculated from the ratio of weight loss to density and the wear rate was calculated from wear volume divided by sliding distance. The data for the wear tests were taken from the average of the three measurements. The worn surfaces were cleaned thoroughly to remove the loose wear debris and then observed using optic and scanning electron microscopy (SEM). In the wear tests, wear volume, coefficient of friction, microhardness, optical and SEM were studied to determine the effect of the particle size. The Vickers hardness of the Mg-SiO_2 composite samples were determined by the Future Tech Coop. FM 700 machine. The loading was 50 g and the loading time was 10 s.

2.3 Optical and SEM

The microstructure of the composite was examined by optical microscopy with a Nikon ECLIPSE L 150 and SEM with a field emission SEM (FESEM) (Zeiss Supra 50 VP). The composite specimens before the wear test were prepared by standard techniques from 220 to 1,200 SiC paper, 1 μm diamond paste and 0.03 μm alumina to finish. The microscopic examinations of the surfaces of the pin pure Mg and composite samples to the sliding direction (SD) were carried out by optic and SEM to delineate the microstructural changes beneath the worn surfaces of the materials after the wear tests.

3. Results and discussion

3.1 Structural analysis and microstructures

Figure 1 shows the X-ray diffraction (XRD) patterns of magnesium composites using SiO_2 in different particle sizes before (Figure 1(a)) and after (Figure 1(b)-(d)) sintering. The peaks show that all the specimens were transformed to Mg_2Si and MgO and there were no Si and O_2 peaks. In addition, different particle sizes were not changed to Mg_2Si and MgO peaks. Accordingly, SiO_2 particles react completely with magnesium powder to form Mg_2Si and MgO. As Mg_2Si and MgO, these phases were composed after the sintering, also similar results reported by Kondoh *et al.* (2005).

Figure 1 XRD diffraction patterns of Mg-SiO_2 composites before (a), and after sintering-Mg-SiO_2 MMC -125 μm (b), -10 μm (c), and -500 μm (d)

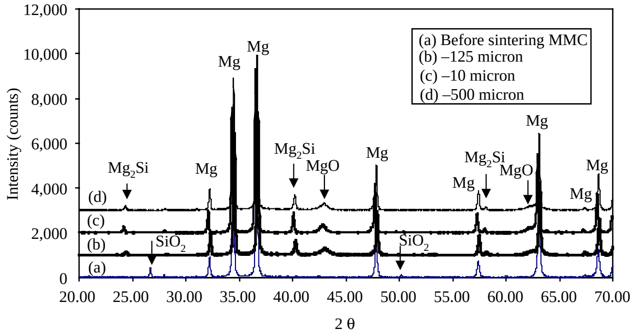
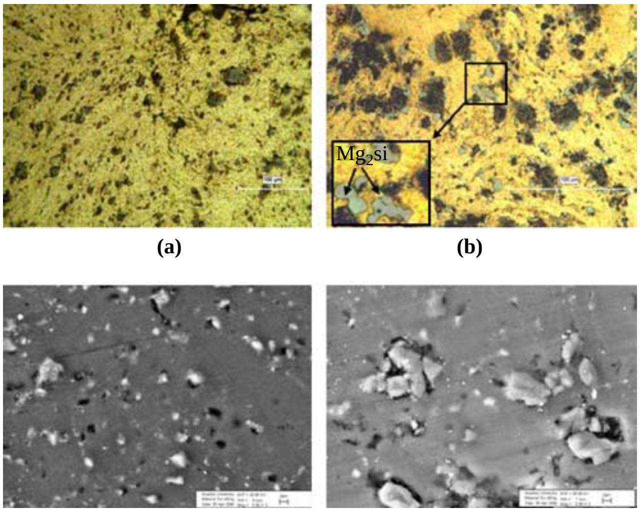


Figure 2(a) and (b) shows the optical microstructure of the pressed and sintered Mg-SiO_2 composite, when Mg-5 wt% SiO_2 -10 μm (a) or -500 μm (Figure 2(b)) particle sizes was employed. The SEM images of composites are shown in Figure 2(c) and (d). As can be seen in the figure, they are uniformly distributed in the matrix. As seen in Figure 2(d), the -500 μm powders were cracked, crumbled and the particle size was also decreased during the high ball milling. The results show that the phase sizes of Mg_2Si and MgO increase with elevations in the SiO_2 particle sizes. However, no increment in the composite structure volume was observed.

Figure 2 The images of Mg-SiO_2 MMC materials, optic -10 μm (a), -500 (b), and SEM images of -10 μm (c), -500 μm (d) particle size



(a) (b)

(c) (d)

3.2 Microhardness test

The microhardness of the pure Mg and Mg-SiO_2 composites after the sintering are shown in Figure 3. As shown in the figure, all of the SiO_2 reinforced composite materials have a higher microhardness value than the pure Mg. Despite the pure Mg, the hardness of the composite was increased in ratio of 70 per cent with the distribution of the Mg_2Si and MgO phases into the Mg matrix. As shown in Figure 1 (XRD patterns), the Mg_2Si and MgO phase intensity was not increased with the increment of particle size.

3.3 The effect of speed and sliding distance on the wear volume

The effect of the application of 5, 10 and 20 N on loads the wear volume loss is shown in Figure 4. It was found that the pure Mg has a higher wear value than the composite materials. From the composite materials, $-500\,\mu m$ SiO_2 particle reinforced composite has a higher wear value but $-10\,\mu m$ particle reinforced composite has a lower wear value. It is evident from Figure 4 that the wear volume increases as the normal load is increased for all the materials at 5, 10 and 20 N loads. The composites show a lower wear rate than the pure magnesium at lower loads. The wear of the composite was linearly increased with the increment of the load. The Mg_2Si and MgO phases that dispersed into the composite structure decreased the wear to the composite.

To determine the effect of reinforcing particles on the wear resistance of the materials, the wear volume was plotted against SiO_2 particle size at a speed of $1.0\,ms^{-1}$ (Figure 4). As can be inferred from the graph, at 5, 10 or 20 N loads, the -500, -250, -125, -75 and $-10\,\mu m$ SiO_2-reinforced composite showed higher wear resistance as compared to unreinforced pure Mg.

Figure 3 The microhardness (HV) of the pure Mg and Mg-SiO_2 MMC parts at the 50 g, 10 s after the sintering

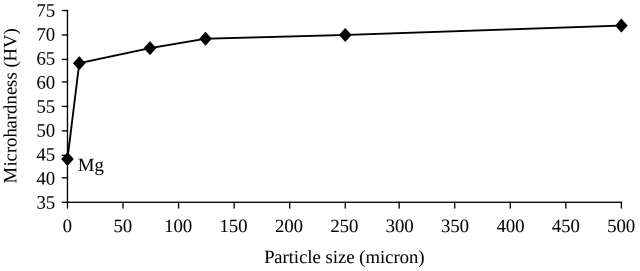
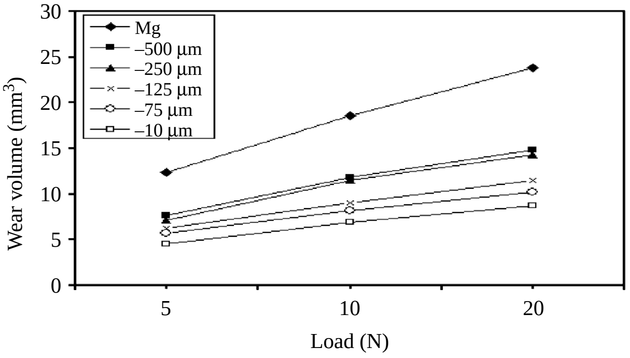


Figure 4 The wear volume loss at different loads at a speed of $1.0\,ms^{-1}$, for Mg and composites



The wear volume in terms of mm^3 for the pure magnesium ($40\,\mu m$) and its composite reinforced with 5 wt% SiO_2 (different particle sizes of -500, -250, -125, -75 and $-10\,\mu m$) are plotted against the load for different speeds of 0.5, 1.0 and $2.0\,ms^{-1}$ (Figure 5). It can be seen that the wear volume of both the unreinforced pure Mg as well as the composite specimens increases with the increment of sliding speed. This result is consistent with a previous study (Mondal *et al.*, 2007). It may be noted that the composite specimens exhibited significantly lower wear volume than the base Mg specimens. The wear volume of each composite specimen reduces with a decrease in the particle size from -500 to $-10\,\mu m$ in the matrix. It can be seen that as Mg_2Si and MgO phases dispersed homogenous into the matrix, the wear resistance was improved, confirming the positive effect of the reinforcing SiO_2 particles as well as its content or particle size in reducing the wear rate of materials. As shown in Figure 5, despite the pure Mg, the wear resistance of the composite ($-10\,\mu m$ particle size) was increased in ratio of 60 per cent.

3.4 Coefficient of friction and temperature

Figure 6 shows the dependence of the coefficient of friction (μ) on the sliding distance of the magnesium and its composite with Mg_2Si-MgO dispersions. In the figure, during the initial stage of the test, the composite wears less than the pure magnesium materials. The mean coefficient of friction for all tests was within the range 0.446-0.308. While the coefficient of friction for pure Mg have a higher wear value, the friction coefficient of $-10\,\mu m$ particle size sample was decreased. On the other hand, as shown in Figure 6, the composite sample which has a $-10\,\mu m$ particle size has lower surface roughness (Ra 0.174) after the wear process. Owing to the decreases in the reinforced particle size, both the coefficient of friction and the surface roughness were also decreased. Therefore, the wear volume of the composite lowers upon dry wear process.

Figure 7 shows the effect of different sliding distances on the temperature at various sliding seeds (0.5, 1.0 and $2.0\,ms^{-1}$). In the figure, when the sliding speeds are increased, the temperature of the composite surfaces increases. Therefore, the wear volume of the composite parts increases with the increment of sliding distance and speeds.

Figure 5 The changes of wear volume loss at different sliding speeds

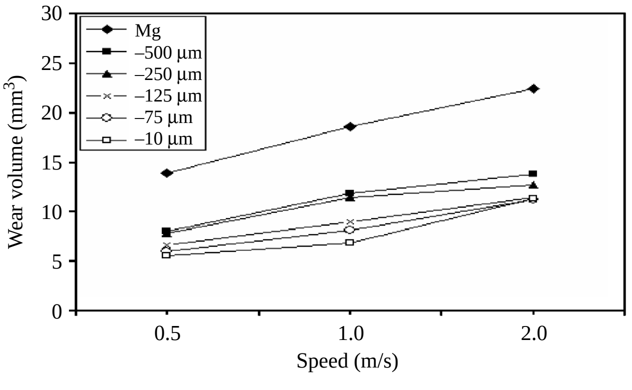


Figure 6 The changes in coefficient of friction during wear test as a function of sliding distance

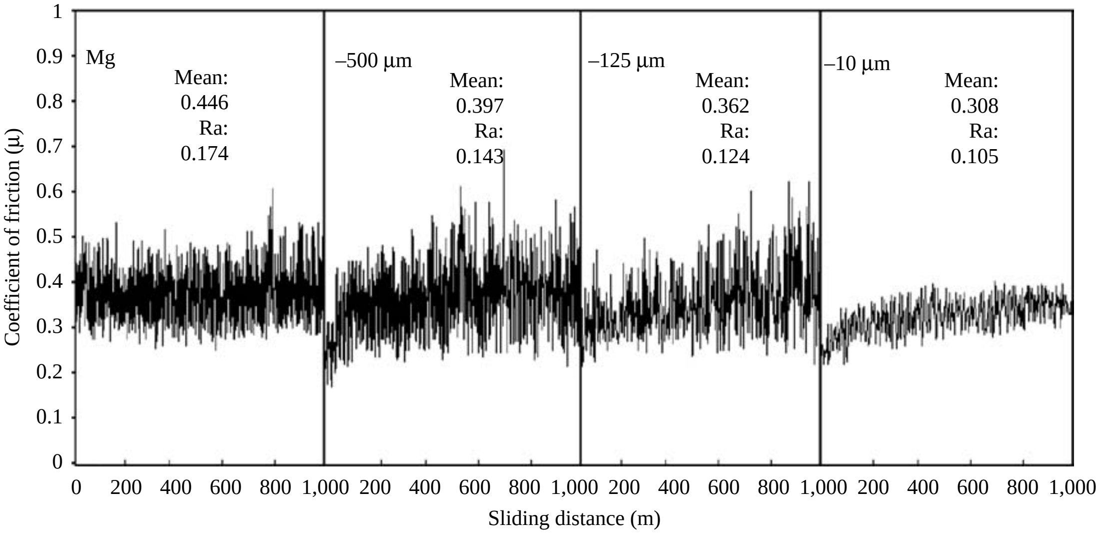
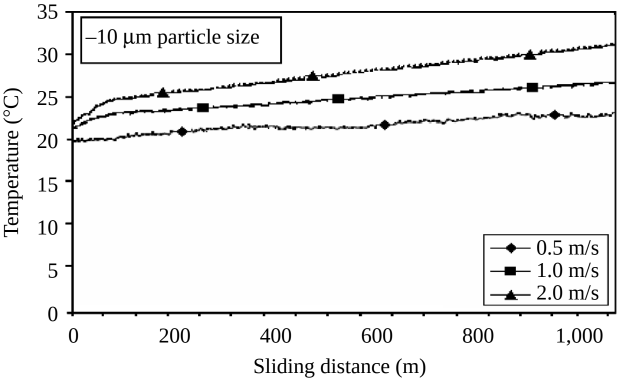


Figure 7 The effect of sliding distance on temperature at different sliding speeds



3.5 Morphology of the worn surfaces

The worn surfaces of all the composite specimens (−10, −75, −125, −250 and −500 μm particle sized SiO_2-reinforced) were covered with grooves (Figure 8). Differences in the extent of the grooving for different particle sizes were observed with well-defined deep grooves. In Figure 8(b), at the 10 N loads, the −10 μm particle sized composite have shallow scratches made by the plastic deformation. The deeper grooves indicate that there was a coarse particle size in the matrix. In composite specimens, rough wear surfaces were produced. The SEM examination of the worn surfaces shows the areas from where material has been removed (Figure 8(a)). The sliding surface of every pin specimen shows slight wear tracks by abrasive wear. It is clear that the damaged area due to plugging wear increases with an increase in the SiO_2 particle size. Furthermore, as shown in Figure 9, the attacking or plugging by the Mg_2Si-MgO dispersoids protruding from the pin specimen surface increases the wear of the counter materials (disc materials). According to these results, the coarse-grain SiO_2 particles in the matrix are created deeper and wider than the wearing traces. Therefore, for the −500 μm particle size, the surface roughness value and wearing are higher than for the −10 μm particle size. The composite specimens show a mixed abrasive-plastic deformation mechanism as is evident

Figure 8 The SEM images of the wear surfaces of the pure Mg and Mg-5 wt% SiO_2 composite during the 1.0 ms^{-1} sliding speed and under the 10 N load, pure Mg (a), −10 μm (b), −75μm (c), −125 μm (d), −250 μm (e), and −500 μm particle size (f)

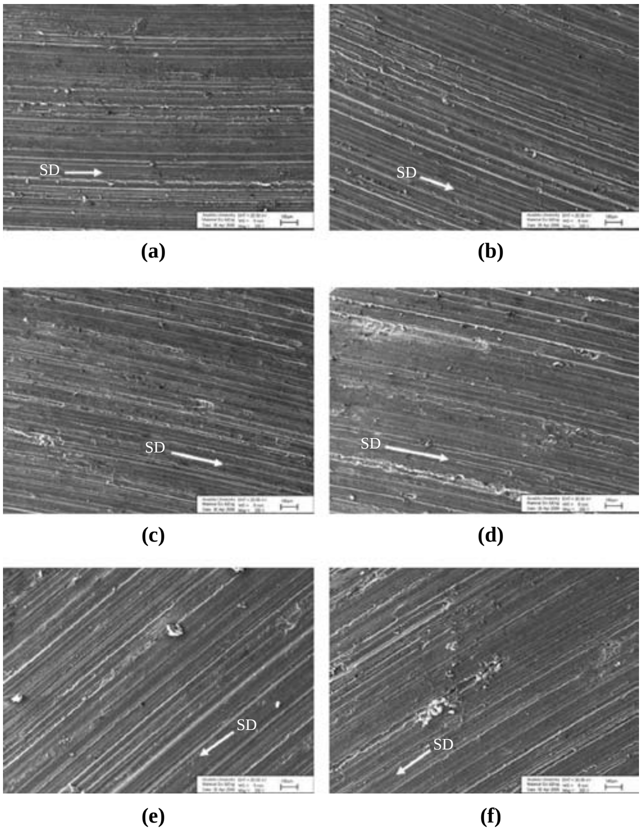
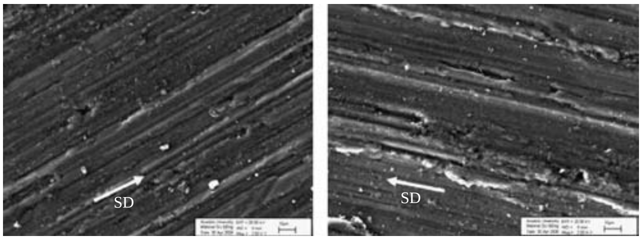


Figure 9 Magnified view of Figure 8(b) ($-10\,\mu$m) (a) and Figure 8(f) ($-500\,\mu$m) (b)



(a) (b)

from Figure 9. The material removal during the process is in the form of small pieces resulting in the formation of flake-type debris. Together, the above result suggests that the main wear mechanism at high speeds is delamination wear, causing excessive fracture of the reinforcement and the matrix. Thus, this results in deterioration of the wear resistance of the composite.

Figure 8 shows low-magnification images of the worn surfaces of the unreinforced pure Mg and its composites, tested at $1.0\,\mathrm{ms}^{-1}$ sliding speed under 5, 10 and 20 N loads and different SiO_2 particle sizes. A magnified view is seen in Figure 9. In Figure 8(a), the micrographs of the unreinforced alloy at 10 N reveal that numerous continuous shallow fine grooves had formed on the wear surfaces. These parallel grooves are the proof of micro plugging. However, there are hardly any grooves visible on the surface of the composite due to the higher load-bearing capacity of the composite, which is responsible for the lower wear rate of the composite at a lower load. When the SiO_2 particle size is increased from -10 to $-500\,\mu$m, the surface of the composite specimens also show a number of grooves, but these are finer than those in the pure Mg at the corresponding load and speed. The SEM views of the worn surface of the 5 wt% SiO_2 $-500\,\mu$m composite tested at 10 N loads are shown in Figure 8(b). This figure shows small particles which are the embedded fragments of detached hard particles. It is observed that the severely deformed material layers are extruded along the SD and flow out of the contact surface of the samples. These layers often reached a length of up to 2-3 mm before detachment and they were curled due to the ductility of the pure Mg, whereas hardly any curling was observed for the composite. Though the micro-shallow grooves are broader in the case of pure Mg, the composites show the presence of broken SiO_2 particles, which are responsible for the additional abrasion of the $-500\,\mu$m SiO_2-reinforced composite.

4. Conclusions

In this work, pure Mg powder with purity of 99.9 per cent and SiO_2 powders with a mean particle size of -500, -250, -125, -75 and $-10\,\mu$m were mixed by mechanical alloying. The wear behaviour of Mg-SiO_2 composite, with the different particle sized composites dispersed with Mg_2Si and MgO intermetallic phases under dry friction condition was studied. The microstructural and mechanical properties of composite material samples were determined by DSC, XRD, microhardness, optical and SEM tests. The following results were obtained from the experimental studies:

- The ceramic SiO_2, which has different particle sized reinforced pure Mg-SiO_2 composites, was produced by powder metallurgy using high ball milling, pressing and sintering.
- Mg_2Si and MgO intermetallic phases produced by powder metallurgy in the Mg-SiO_2 composite are dispersed as homogeneous into the Mg matrix after the sintering.
- The ceramic SiO_2 particle reinforced Mg-SiO_2 composites exhibited a lower wear rate than the unreinforced pure magnesium specimens.
- Despite the pure Mg, the wear resistance of the composite (reinforced with $-10\,\mu$m particle size) was 61 per cent and the wear volume decreased with reducing SiO_2 particle size.
- The wear volume of the composites as well as the pure Mg increased with the increment of applied load. Likewise, the wear volume of the composites as well as the pure Mg increased with the increment of sliding speed.
- The composite materials exhibited abrasion wear at low loads; however, at high loads the delamination wear was observed.
- The hardness of the composite was increased in a ratio of 70 per cent with the distribution of the Mg_2Si and MgO phases into the Mg matrix.
- The wear volume of composite parts is increased in parallel to the sliding distance and sliding speeds.

References

Alahelisten, A., Bergman, F., Olsson, M. and Hogmark, S. (1993), "On the wear of aluminium and magnesium metal matrix composites", *Wear*, Vol. 165 No. 2, pp. 221-6.

Kondoh, K., Tsuzuki, R. and Yuasa, E. (2005), "Tribological properties of magnesium matrix composite alloys dispersed with Mg_2Si particles", *ATM-Advances in Technology of Materials and Materials Processing Journal*, Vol. 7 No. 1, pp. 33-6.

Kumar, B.V.M., Basu, B., Murthy, V.S.R. and Gupta, M. (2005), "The role of tribochemistry on fretting wear of Mg-SiC particulate composites", *Composites Part A*, Vol. 36, pp. 13-23.

Lim, C.Y.H., Lim, S.C. and Gupta, M. (2003), "Wear behaviour of SiCp-reinforced magnesium matrix composites", *Wear*, Vol. 255, pp. 629-37.

Lu, L., Lai, M.O. and Hoe, M.L. (1998), "Formation of nanocrystalline Mg_2Si and Mg_2Si dispersion strengthened Mg-Al alloy by mechanical alloying", *Nanostructured Materials*, Vol. 10 No. 4, pp. 551-63.

Lu, L., Tong, K.K. and Gupta, M. (2003), "Mg-based composite reinforced by Mg_2Si", *Composites Science and Technology*, Vol. 63, pp. 627-32.

Mabuchi, M., Kubota, K. and Higashi, K.K. (1996), "Elevated temperature mechanical properties of magnesium alloys containing Mg_2Si", *Materials Science and Technology*, Vol. 12, pp. 35-9.

Mondal, A.K., Chandra Rao, B.S.S. and Kumar, S. (2007), "Wear behaviour of AE42+20% saffil Mg-MMC", *Tribology International*, Vol. 40, pp. 290-6.

Sharma, S.C., Annand, B. and Krishma, M. (2000), "Evaluation of sliding wear behaviour of feldspar particle-reinforced magnesium alloy composites", *Wear*, Vol. 241, pp. 33-40.

Wang, L., Qin, X.Y., Xiong, W. and Zhu, X.G. (2007), "Fabrication and mechanical properties of bulk nanocrystalline intermetallic Mg_2Si", *Materials Science Engineering A*, Vol. 459, pp. 216-22.

Wei, X., Xiao-Ying, Q., Ming-Guang, K. and Li, C. (2006), "Synthesis and properties of bulk nanocrystalline Mg_2Si though ball-milling and reactive hot-pressing", *Transactions of Nonferrous Metals Society of China*, Vol. 16, pp. 987-91.

Corresponding author

Fehim Findik can be contacted at: fehimfindik@gmail.com