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Dry tribological behavior of Mg/SiC_p composites at room and elevated temperatures

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Pure magnesium and its composites reinforced with 5, 10 and 15 vol% SiC particulates with a mean diameter of 7.8 μm were fabricated by a powder metallurgy process. The tribological behavior of the samples was investigated under normal loads of 5–60 N at sliding speed of 0.4 m/s and at wear temperatures of 25–200 °C. At the wear temperature of 25 °C, results showed almost close wear rates under normal loads of 5 and 20 N. However, under higher normal loads the composites showed lower wear rate than that of the unreinforced magnesium. At the higher wear temperatures of 100, 150 and 200 °C, a significant lower wear rate was observed for the composites compared to the pure magnesium. Increasing the normal load resulted in a transition from mild to severe wear at all wear temperatures. Below the transition load oxidation was a dominant wear mechanism, while above that severe plastic deformation and adhesion were the main wear mechanisms. The results also showed wear rate improvement of the composites with increasing SiC content. Finally, a wear map showing mild and severe wear regimes as a function of load and wear temperature was adopted for the composites.

1. Introduction

Development of new structural materials with higher strength-to-weight ratios is one of the biggest challenges in transportation industry to reduce fuel consumption and greenhouse gas emissions [1]. Magnesium with low density, good castability, high specific strength, and reasonable cost can be considered as a candidate to be used as a lightweight structural material such as bearings, moving parts and engine parts. The main problem, which sidelined magnesium from these applications, is its poor strength especially at high temperatures, which can cause structural failure by reducing fine tolerance and destroying surface finish of components during sliding [2,3]. One of the effective approaches to improve high temperature mechanical and wear properties of magnesium-based matrix is adding thermally stable ceramic reinforcements (fibers or particles) [4–10]. Magnesium-based composites are currently being explored for a number of high-temperature applications such as automotive engine parts, oil pump covers, cylinder liners, aircraft engine castings and various wear resistant applications [11].

One of the early attempts to study wear behavior of magnesium dates back to 1991 by Hiratsuka et al. [12]. They investigated dry sliding wear of pure magnesium against an alumina counterface using a pin on disc test. They observed two different wear mechanisms depending on the testing environment. Magnesium exhibited an oxidation wear mechanism when tested in air. However, in vacuum, magnesium showed metallic lustre with high wear rate. The wear behavior of AZ91 alloy at room and elevated temperatures was studied by Zafari et al. [13]. They investigated mild and severe wear regimes of AZ91 at different loads and temperatures. They also studied the effects of 1–3 wt% lanthanum-based rare earth (RE) additions on the wear behavior of AZ91 alloy at the wear temperature of 25–250 °C [14,15]. It has been shown that at a wear temperature of 25 °C all specimens had a similar wear behavior. At a wear temperature of 100 °C, AZ91 alloy showed lower wear rate than the RE containing alloys due to the formation of compact oxide patches on the worn surface of AZ91 alloy and the creation of secondary β-$Mg_{17}Al_{12}$ precipitates beneath the worn surface. However, by increasing temperature from 100 °C to 150 °C and 200 °C AZ91 alloy showed severe plastic deformation and adhesion, while higher strength RE containing alloys maintained the tribological layers on the wear surface and showed lower wear. The sliding wear study on AZ91 alloy reinforced with feldspar particles (silicate composed of aluminosilicate of sodium, potassium, and calcium with hardness of nearly equal to SiC) was conducted by Sharma et al. [11]. They found that wear rates decreased with increasing reinforcement content. A transition from mild to severe wear with increasing load was noted, but the presence of the feldspar particles was able to delay this transition. Lim et al. [16] have also studied the wear behavior of AZ91

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reinforced with SiC particles in a dry sliding wear test. They reported that the addition of the reinforcement was beneficial only at lower loads. Habibnejad et al. [17] have studied tribological behavior of pure magnesium and AZ31 magnesium alloy strengthened by Al_2O_3 nanoparticles. They found that wear rates decreased with increasing reinforcement content. They attributed improved wear behavior to composite strengthening mechanisms like load bearing ability of hard particles and mismatch hardening mechanism. Some studies also indicate that SiC particles have a good stability in magnesium matrix and make Mg/SiC a better material choice over Al/SiC [18]. Furthermore, SiC particulate reinforcements prove to be a relatively economical reinforcement [19]. The aim of the present study was to investigate the effects of wear temperature and normal load on the wear behavior of powder metallurgy processed magnesium composite reinforced with various volume fractions of SiC particles.

2. Experimental details

Magnesium composites reinforced with 5, 10 and 15 vol% SiC particulates were prepared from elemental powders. The mean diameter of magnesium and sharp edged SiC powders was about 75 µm and 7.8 µm, respectively. Magnesium and SiC particulates were mixed in a blender at a rotational speed of 42 rpm for 2 h. The powder mixture was cold compacted on a 100-ton capacity, electrically driven hydraulic pressing machine to a size of 50 mm height and 42 mm diameter cylinder. The green compact was then hot pressed at 380 °C and maintained under the load for 15 min. Subsequently, the hot compacted perform was extruded through 11 mm square cross section die at 350 °C. Pin specimens of 5×5 mm^2 in cross-section and 10 mm in length were machined using an electro-discharge wire-cut machine from the square cross section extruded rods, for wear tests.

The strength of the materials was assessed by the shear punch test (ASTM:D732) in the temperature range of 25–225 °C, using a screw driven material testing system with a crosshead speed of 0.25 mm min^{-1}, the details of which are given elsewhere [20]. Hot hardness tests were also performed in the temperature range of 25–250 °C using a SANTAM universal testing system equipped with a three-zone split furnace. A cemented-carbide Vickers indenter was mounted in a holder positioned in the center of the vertical loading bar. The specimen was located on an anvil below the loading bar; the assembly of the specimen and the indenter was accommodated by a split furnace. To stabilize the temperature, specimens were held at each temperature for 15 min before the onset of hardness measurements. A load of 20 N at a rate of 0.5 mm min^{-1} was applied for a dwell time of 30 s. At least three indentations were made on each sample and the lengths of the diagonals were quantified by an optical microscope.

Dry sliding wear tests were performed in the direction perpendicular to the extrusion direction. Pin-on-disk wear tests were performed at the wear temperatures of 25, 100, 150 and 200 °C. A resistant split furnace with an accuracy of ± 5 °C was used to achieve a desired temperature on both pin and disc. To stabilize the temperature, pin and disc specimens were held at each temperature for 20 min before the onset of the high temperature wear tests. The counterface was AISI/SAE 52100 steel disk, 40 mm in diameter and 5 mm in thickness, with a hardness of 60 HRC (697 HV 30 kg) and an average roughness (R_a) of 0.52 µm. The pins were polished to the surface roughness (R_a) of about 0.2 µm. Prior to each wear test, both the disk and the pin were ultrasonically cleaned with acetone to remove any possible traces of contaminants. Moreover, the pins were in a conformal contact with the disks. The volume wear loss was measured by determining the height difference of the pins during sliding using a digital precision micrometer with the accuracy of 1.0 µm. The wear tests were conducted under normal loads of 5, 20, 40, 60 and 80 N at a constant sliding speed of 0.4 m s^{-1} for a sliding distance of 1000 m. The normal loads were applied by a pneumatic loading device in which a specific pressure was applied on one side of a piston to obtain a desired load on the pin.

The microstructure of the tested samples, the steel counterface and morphology of the wear surfaces were studied by scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS). X-ray diffraction (XRD) analysis was also carried out on samples in the 2θ range of 20–120° with the low scanning rate of 1°/min.

3. Results and discussion

3.1. Microstructural characterization

Fig. 1 shows a typical microstructure of each composite on a section cut perpendicular to the extrusion direction. It is apparent that the distribution of particles throughout the matrix was uniform. The volume fraction of particles determined from image analysis of several micrographs was found to be 4.6, 10.1, and 14.5 vol% for Mg–5% SiC, Mg–10% SiC, Mg–15% SiC, respectively. The XRD pattern of Mg–15% SiC composite is shown in Fig. 2. The pattern indicates that magnesium and SiC were the main constituents of the composites. However, two relatively weak peaks at about $2\theta = 43°$ and 110° are indicative of the presence of MgO. The quantitative analysis of MgO was performed in two different ways. First, according to the average weight percent of 2.5 for oxygen obtained from EDS analysis of Mg–15% SiC sample, the weight percent of MgO was calculated as 6.5%. Another approach for determining the amount of MgO was by a bulk extraction method, in which a pre-weighted sample was dissolved in HCL to extract the base Mg matrix and to leave the insoluble MgO and SiC. Knowing the amount of SiC, the weighted MgO was found to be about 6%. This weight percent corresponded to the volume percent of about 3.4.

3.2. Mechanical properties

The temperature dependence of the hardness values for the pure magnesium sample and its composites is shown in Fig. 3. The graph is plotted on a semi-logarithmic scale due to an exponential relation between hardness and temperature [21,22]. It can be observed from Fig. 3 that at each test temperature the hardness values of composites increased with increasing SiC_p volume fraction. As an example, at the test temperature of 25 °C, Mg–15% SiC composite showed 50% improvement in the hardness comparing to the pure magnesium. The hardness variation with temperature (Fig. 3) also revealed two distinct regions namely, (i) a gradual decrease of hardness up to a temperature of about 150 °C and (ii) a sharper drop in hardness above 150 °C. The sharp decrease in hardness values above 150 °C is ascribed to the softening behavior of the matrix, and weakening of the matrix–reinforcement interface bond, by which load transfer from matrix to reinforcements diminishes [23]. The transition between low and high temperature behavior could be obtained from the intersection of the respective fitted lines. It can be deduced from Fig. 3 that this temperature was 133 °C for pure Mg which increased to 150 °C after addition of 15% SiC. As the transition temperature is indicative of a deformation mechanism, a higher transition temperature implies that the material withstand deformation up to higher temperatures [22].

Fig. 4 illustrates the shear yield strength of the pure magnesium and its composites at the test temperatures between 25 and 225 °C. According to this figure, shear yield strength of the