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Tribology characteristics of magnesium alloy AZ31B and its composites

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ABSTRACT

In this paper, wear characteristics of magnesium alloy, AZ31B, and its nano-composites, AZ31B/nano-Al_2O_3, processed by the disintegrated melt deposition technique are investigated. The experiments were carried out using a pin-on-disk configuration against a steel disk counterface under different sliding speeds of 1, 3, 5, 7 and 10 m/s for 10 N normal load, and 1, 3 and 5 m/s for 30 N normal load. The worn samples and wear debris were then examined under a field emission scanning electron microscopy equipped with an energy dispersive spectrometer to reveal its wear features. The wear test results show that the wear rates of the composites are gradually reduced over the sliding speed range for both normal loads. The composite wear rates are higher than that of the alloy at low speeds and lower when sliding speed further increased. The coefficient of friction results of both the alloy and composites are in the range of 0.25–0.45 and reaches minimums at 5 m/s under 10 N and 3 m/s under 30 N load. Microstructural characterization results established different dominant mechanisms at different sliding speeds, namely, abrasion, delamination, oxidation, adhesion and thermal softening and melting. An experimental wear map was then constructed.

1. Introduction

Global efforts to reduce carbon dioxide gas emission and the uncertainty over oil prices have been pushing scientists to look for alternative solutions. One of these is to use the environmentally friendly light weight components and magnesium is the best candidate due to its lightness and strength. Magnesium has a density of 1.74 g/cm^3 which is approximately two thirds that of Al (2.7 g/cm3), one fifth that of steel (7.9 g/cm^3) and in close comparison to that of plastics (0.92–2.17 g/cm^3) [1]. Magnesium also possesses good castability, high damping capacity, recyclability and dimensional stability, in addition to having comparable absolute strength value to Al, and requiring less energy for production compared to Al. Magnesium materials are thus attractive for many applications, particularly in automobiles, aerospace, defense and sports industries. Despite its advantages, the use of magnesium based structural materials is still largely limited by its low stiffness and ductility, inadequate creep resistance at elevated temperatures and low electrical potential making it particularly prone to corrosion. These limitations are often circumvented through the addition of reinforcements to form a composite, or the addition of suitable alloying elements to form an alloy or through coatings [1,2]. In certain applications, the components made from these composites or alloys are subjected to sliding movements resulting in the possibility of wear damage. This paper, thereby, studies tribological characteristics of AZ31B alloy and its composites.

The literature search shows number of works which has been done to understand dry sliding wear characteristics and mechanisms of magnesium based materials [3–6]. Wear behaviors are dependent on sample materials, counterface materials and its surface finish as well as testing conditions including the applied load, sliding speed and test environments. Rams et al. [7] constructed a wear map for AM60B magnesium alloys at loads ranging from 10 N to 250 N and sliding speeds from 0 to 1 m/s. At lower loads, the wear mechanisms were dominated by oxidation, delamination and adhesion while at high loads the mechanism changed to severe plastic deformation. Somekawa et al. [6] studied the wear behavior of pure Mg and Mg–Y alloy and the microstructural evolution during the wear test. The wear rate of alloy was superior than that of pure Mg and twining formation {10–12} occurred during the test. Surface treatments such as plasma electrolytic oxidation coating and PVD coating were used to improve wear properties of magnesium materials [8]. In addition, the effects of some oxide and carbide reinforcements on wear of magnesium materials were investigated [9–11]. However, the literature search shows that no work has so far been done to study the wear characteristics of AZ31B and AZ31B/nano-Al_2O_3 composites.

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Accordingly, the aim of the present study is to develop a better understanding of the wear characteristics of AZ31B and AZ31B/nano-Al_2O_3 composites processed by the disintegrated melt deposition technique.

2. Experimental procedures

2.1. Materials

The AZ31B alloy matrix used in this study has a chemical composition of 2.94 wt% Al, 0.87 wt% Zn, 0.57 wt% Mn, 0.0027 wt% Fe, 0.0112 wt% Si, 0.0008 wt% Cu, 0.0005 wt% Ni, and Mg balance. Three volume percentages of 50 nm-sized Al_2O_3 particulates, 0.66 vol%, 1.11 vol% and 1.50 vol%, were chosen as reinforcements. Synthesis of monolithic and reinforced composites was carried out using the disintegrated melt deposition technique, followed by machining and hot extrusion to 8 mm diameter rods. Pin specimens for wear tests were machined to 5 mm diameter and 17 mm length from the extruded rods. Pin contact surfaces were ground against 600 grit silicon carbide, subsequently cleaned with alcohol and then air dried. Mechanical properties, microhardness and microstructural characterization were reported elsewhere [12].

2.2. Wear testing

Dry sliding wear tests were carried out on AZ31B alloy and AZ31B/nano-Al_2O_3 composites using a pin-on-disc configuration against a rotating 63 HRC oil-hardened tool steel counterface in accordance to the ASTM test standard G99-05 [13]. Cylindrical pin specimens of 5 mm diameter and 17 mm length were loaded vertically onto a stationary pin holder. Test conditions included load–speed settings of 1, 3, 5, 7 and 10 m/s sliding speeds under a 10 N normal load, and 1, 3 and 5 m/s speeds under 30 N load. For each sliding condition, five runs of 600 m each were conducted, using a constant track radius of 95.49 mm. During each run, strain gauges mounted in a full-bridge configuration on the cantilever arm of the apparatus recorded friction coefficient values (COF) at every 0.1 s time interval. Apart from friction data, vibration and noise characteristics as well as naked eye observation of worn pin surfaces were recorded during and after each run respectively. All experiments were conducted in air with temperature and relative humidity maintained between 22 ± 1 °C and $75 \pm 5\%$ respectively.

Prior to each run, the steel counterface was ground with 320-grit and then 600-grit SiC abrasive for several minutes to remove accumulated wear debris and material transferred from the pins, followed by cleaning with alcohol. At the end of each run, any extruded material flow and flaring around the pin edges were carefully filed off under an optical microscope and the pin specimens were cleaned with alcohol before weighing using an electronic balance with ± 0.01 mg accuracy. Data collected and analyzed include wear rates in the form of mass loss and coefficient of friction values. Worn specimen surfaces and accompanying wear debris were examined using Field Emission Scanning Electron Microscopy (FESEM-4300) equipped with Energy Dispersive X-ray Spectroscopy (EDS).

3. Results and discussion

3.1. Wear rates

Fig. 1 shows the volumetric wear rates of AZ31B and its composites at different sliding speeds and loads. The wear rates of both AZ31B and composites gradually reduced to a minimum at a critical speed (~5 m/s and 10 N or 3 m/s and 30 N). Subsequently, above these critical speeds, the wear rate of AZ31B went up while the wear rates of composites decreased modestly. In addition, the increment in normal load led to higher wear rates and a lower critical speed where the wear rates were minimum.

The gradual reduction in wear rates at low speeds is mainly attributed to frictional heating. At the lowest speed of 1 m/s, wear rates are the highest due to abrasive micro-cutting and delamination. As sliding speeds increased, frictional heating causes surface flash temperatures to rise [14], activating additional slip planes thereby promoting greater ductility. In addition, the oxide films that formed at these low sliding speeds, albeit only partial and discontinuous, were minimally beneficial in reducing true metallic contact of the wearing surfaces. This can also be one of the causes for the initial steep decline in wear rates. Further, it is observed from Fig. 1 that at low speeds the wear rates of composites are higher than that of AZ31B and increased with the increase in amount of nano-alumina. This is mainly attributed to lower yield strengths of the composites [3,11].

At higher speed (5–10 m/s and 10 N or 3–5 m/s and 30 N), the monolithic alloy AZ31B displays a gradual but consistent climb in wear rates while the composites exhibit a correspondingly opposite, modest but consistent decrease in wear rates. Within this range of sliding speeds, continued sliding under more extreme conditions induces even larger rises in surface flash temperatures [14]. The primary wear mode in all materials was observed to change from adhesive wear to thermal softening and melting. Besides inducing material transfer away from the pin surfaces like in adhesive wear, thermal softening and melting further cause bulk plastic deformation of the wearing surface. The reasons for the modest decline in wear rates for the composites can be found in their previously noted ability to delay thermal wear to higher loads and speeds due to the presence of ceramic particles particularly nano-alumina [3,4,11].

3.2. Friction coefficient values

For all materials tested under both 10 N and 30 N, the COF values for each material display a similar distinct trend compared to that of wear rate – first, a decline up to a critical speed, followed by a subsequent increase (Fig. 2). The critical speeds at which the COF values for all materials achieve a minimum under both loads is observed to coincide with the same critical speeds which elicit generally the lowest wear rates as well (5 m/s under 10 N and 3 m/s under 30 N load). The results of friction coefficient are comparable, in principle, with those of aluminum based composite materials [15].

The initial decline in COF values can be attributed to general softening of the pin surfaces with increased frictional heating. Bowden and Taylor's model for friction [16] regard friction as the force which must be overcome to break the bonding due to local welding and adhesion as asperities from contacting surfaces interact. Consequently, with increased sliding speed, greater frictional heating causes pin surfaces to grow progressively weaker first at local hot-spots [14], and therefore allows easier shearing of these bonded contact zones at the interface [17], leading to the initial general decline in COF values across all samples. This is also probably one reason why the same increase in sliding speed causes an accompanying wear mode transition to one which is primarily adhesion-dominated as well. With further increase in sliding speed however, the even greater frictional heating possibly causes surfaces to bulk-soften to a point initiating large-scale conformation of the pin surfaces to the steel counterface under the contact pressures experienced. This is consistent with the attendant wear mode transition to thermal softening and melting, which involves the plastic flow of not only select regions but