

# Wear Mechanisms for Extruded AZ31B Magnesium Alloy during Dry Sliding Condition

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## Abstract

In present work, the wear behaviour of extruded AZ31B magnesium alloy during dry sliding conditions has been investigated. The experiments were carried out using a pin-on-disc type wear apparatus against a steel disc counter face in an applied load range of 10-50 N, sliding velocity range of 0.1-0.9 m/s and at a constant sliding distance of 1000 m. The effect of applied load and sliding velocity on wear rate were analyzed. The wear surfaces were examined using a scanning electron microscope equipped with an energy dispersive spectrometer to reveal wear features. Wear mechanisms were analyzed at different sliding conditions. They were abrasion, oxidation, delamination, plastic deformation and melting.

**Keywords: Magnesium Alloy, Extrusion, Dry Sliding Wear, Wear Rate, Wear Mechanism**

## I. INTRODUCTION

Over the last years, the required emission reduction has caused a continuing demand for lightweight materials in order to reduce weight in aerospace and automotive applications, as well as in components of laptops, mobile phones and household equipment. Among the lightweight metals, Mg and its alloys are of great interest for these industries because their low densities range from 1.75 to 1.85 mg/m<sup>3</sup>, being 30% lower than that of aluminum alloys. Magnesium and its alloys are non-magnetic, have high thermal and electrical conductivity, good vibration and shock absorption ability and high specific strength [1-4]. These characteristics make them an appropriate choice in a number of demanding applications, especially for applications as moving components [5]. Despite of their attractive bulk mechanical properties, magnesium alloys poor resistance to corrosion and wear are serious limitations to widely extend their applications [6, 7].

Cast magnesium alloys fail to meet most of the requirements and the wrought magnesium alloys find extensive application by replacing parts made of aluminium or steel [8]. Recycling of Magnesium alloy yielded fine grained specimens with considerable improvement in hardness and strength. The superior mechanical properties of these alloys suggest their suitability in friction and wear applications [9]. To improve mechanical properties, forming process has been adapted to produce components with a unique microstructure with small spherical primary particles uniformly distributed in the matrix, which is essentially different from those produced by using conventional casting techniques [10, 11]. In addition, forming process can significantly decrease, and even eliminate porosities that easily form in an alloy with wide solidification interval [12]. Guangli et al. [13] investigated the dry sliding wear behavior of extruded Mg-2Dy-0.5Zn alloy using a pin-on-disk configuration. They found five wear mechanisms, namely abrasion, oxidation, delamination, thermal softening and melting. The extruded Mg-2Dy-0.5Zn alloy exhibited the better wear resistance because of fine grain size. Jing Jiang et al. [14] studied the dry sliding wear behavior of extruded Mg-Sn-Yb alloy through pin-on-disc configuration at room temperature. They analyzed the different wear mechanisms for various conditions. They concluded that the wear behavior of extruded alloy have better wear resistance. Anbuselvan et al. [15] studied the wear behavior of extruded ZE41A magnesium alloy using pin on disc configuration. They reported the effect of applied load and sliding velocity on wear rate and discussed the wear mechanisms under various conditions. However, there is still a lack of know-how on the fundamental understanding of wear behaviour and wear mechanisms of magnesium alloys.

In the present work, the dry sliding wear behavior of AZ31B magnesium alloy has been investigated using pin-on-disc type wear apparatus against steel counterface. The effect of applied load and sliding velocity on wear phenomena has been studied. The main wear mechanisms observed were abrasion, oxidation, delamination, plastic deformation and melting.

## II. EXPERIMENTAL PROCEDURES

The material studied was AZ31B magnesium alloy. The chemical composition (wt. %) of the alloy used in this investigation was 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 balance Mg. The brinell hardness of the alloy was 49 (500 kg load) and its density was 1.77 g/cm<sup>3</sup>. Mechanical properties, microhardness and microstructural characterization were reported elsewhere [16]. The microstructure of extruded AZ31B magnesium alloy is shown in Fig. 1.

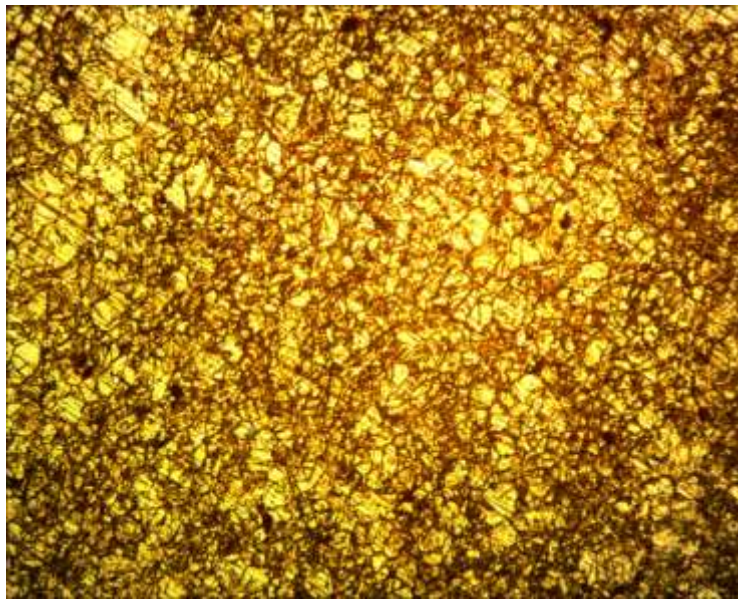


Fig. 1: Microstructure of extruded AZ31B magnesium alloy.

The wear tests were carried out under dry sliding condition in accordance with the ASTM G-99 standard using a pin-on-disc wear testing machine. In the present study, pins of magnesium alloys under investigation were machined to 6 mm in diameter and 20 mm in length. The surface preparation procedure of the wear test samples consisted of grinding surfaces manually by 240, 320, 400 and 600 grit sic papers, respectively and then polished them with 1.0 and 0.05  $\mu\text{m}$  alumina power slurry using a low speed polishing machine. The polished surfaces were cleaned ultrasonically in a methanol solution. The counterface was EN32 steel disc (HRC 65) of 55 mm diameter and 10 mm width having surface roughness of 0.02  $\mu\text{m}$  on which the test specimen slide. The steel disc was cleaned in a methanol solution before each wear test. The tests were carried out in a sliding velocity range of 0.1– 0.9 m/s and a load range of 10–50 N with a constant sliding distance of 1000 m. The mass losses were calculated from the differences in weight of specimens measured before and after the sliding test (after removing any loose debris) using a precision balance (0.001 g). Volumetric wear loss was estimated by dividing the mass loss by the density of the alloy (1.77  $\text{g}/\text{cm}^3$ ). Volumetric wear rate was calculated by dividing the volumetric wear loss by sliding distance. Each test was carried out twice in order to check the reproducibility and average of two tests was taken to determine the wear rate. The deviation between two tests was within 2%. The worn surfaces were examined using scanning electron microscope (SEM) (Model JSM 5610 LV) equipped with energy-dispersive spectrum (EDS). Since the hardness of the counter face was far higher than that of the specimens and its wear volume was very small, the wear properties of the steel disc are not studied in the present paper.

### III. RESULTS AND DISCUSSIONS

The effect of applied load on volumetric wear rate at constant sliding velocity of 0.1, 0.3, 0.5, 0.7 and 0.9 m/s is shown in Fig. 2. It is observed that the wear rate increases with increase in applied load for all sliding velocities. The wear rate increases linearly with increasing applied load up to 30 N. Thereafter, further increases in applied load lead to sudden increase in wear rate. Transition from mild to severe wear occurs at these conditions. This is well agreed with earlier investigation [17]. When the load on the pin is increased, the actual area of contact would increase towards the nominal area, resulting in increased frictional force between two sliding surfaces. The increased frictional force and real surface area in contact will bring about higher wear. Therefore after a critical load there is a transition from smooth linear increase wear rate to sudden increase in wear rate. The effect of sliding velocity on volumetric wear rate at constant applied load of 10, 20, 30, 40 and 50 N is shown in Fig. 3. At all applied load the wear rate increased with increasing sliding velocity. This observation is consistent with the earlier investigation by Sharma et al. [18]. If the sliding velocity increases, the contact temperature also increases due to higher frictional heat and will cause increase in wear rate. The wear rate increases linearly with the sliding velocity up to 0.5 m/s. This linear relationship indicates steady state has been achieved. Further increases in the sliding velocity more than 0.5 m/s, large changes in the slope of wear rate occurred for higher applied loads. Thus indicates that transition from mild to severe wear occurred. Thus the wear rate increased with increase in applied load and sliding velocity.

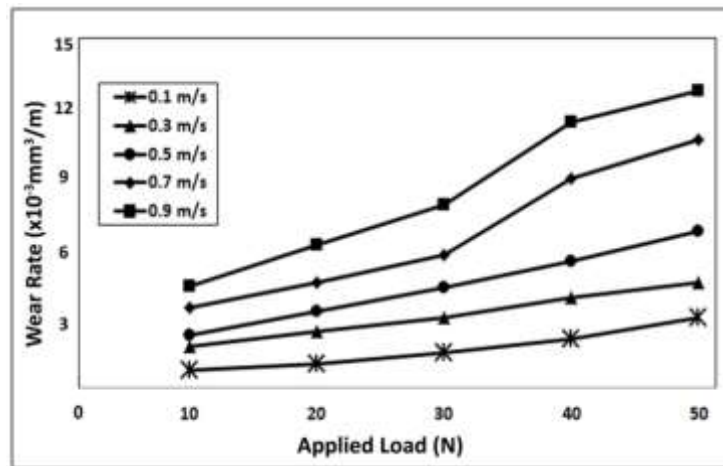


Fig. 2: Effect of applied load on wear rate for various sliding velocities.

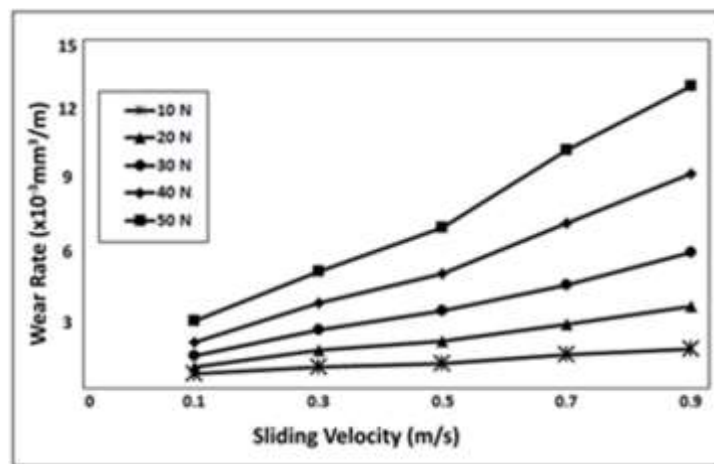


Fig. 3: Effect of sliding velocity on wear rate for various applied loads.

Scanning electron microscope examinations of the worn pin surfaces identified five different wear mechanisms operating under various sliding conditions. They are abrasion, oxidation, delamination, plastic deformation and melting. In the following sections, the observed wear mechanisms are discussed in relation to the sliding conditions and wear rates so as to better understand the tribological characteristics of AZ31B magnesium alloy.

Fig. 4 shows the surface of a pin tested at 20 N of applied load and 0.1 m/s of sliding velocity. It can be observed in the wear surface the presence of many fine grooves aligned, which are the proof of abrasion. These lines are usually caused by the presence of hard particles that plough into the pin. The movement of these particles over the surface cause the removal of material along its path on the surface of the Mg alloy [19]. The formation of grooves mainly results from ploughing and cutting of hard particles between the pin and disc [20]. Aung et al. [21] remarked that the abrasive wear resulted in surface deformation and damage in the form of deep grooves in the sliding direction.

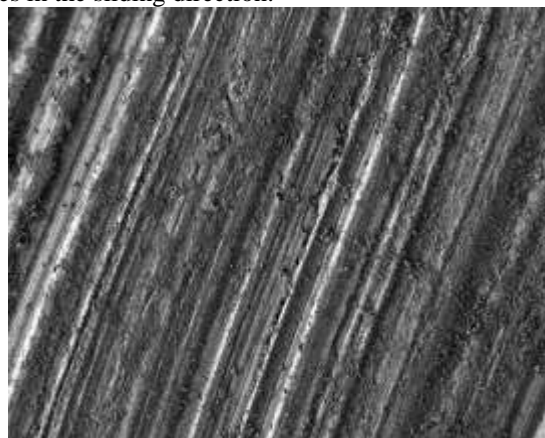


Fig. 4: SEM micrographs showing grooves and scratch marks on the pin surfaces, indicating abrasion at 20 N and 0.1 m/s.

The surfaces of the pins tested under the lower applied load of 20 N and at the lower sliding velocity of 0.3 m/s, appear dark, while those at higher load and higher velocities retain their metallic luster. Fig. 5 shows the oxidation wear and Fig. 6 shows the EDS analysis of oxidation wear. Under SEM, the dark surfaces are found to be covered extensively by a thin layer of fine particles which is shown in Fig. 5. The EDS analysis indicated the presence of a strong oxygen peak in the debris in addition to the magnesium peak is shown in Fig. 6. This wear mechanism is referred as the oxidation wear [22], in which frictional heating during sliding causes oxidation of the surface, with wear occurring through the removal of oxide fragments. Due to repeated sliding, oxide wear debris fills out the valleys on the pin surface, and becomes compacted into a protective layer. So metallic contact is prevented and minimum wear rates are occurred [23]. An et al. [24] reported that the thick oxide layer effectively protected the sliding surface resulting in a mild wear condition with accompanying low wear rate.

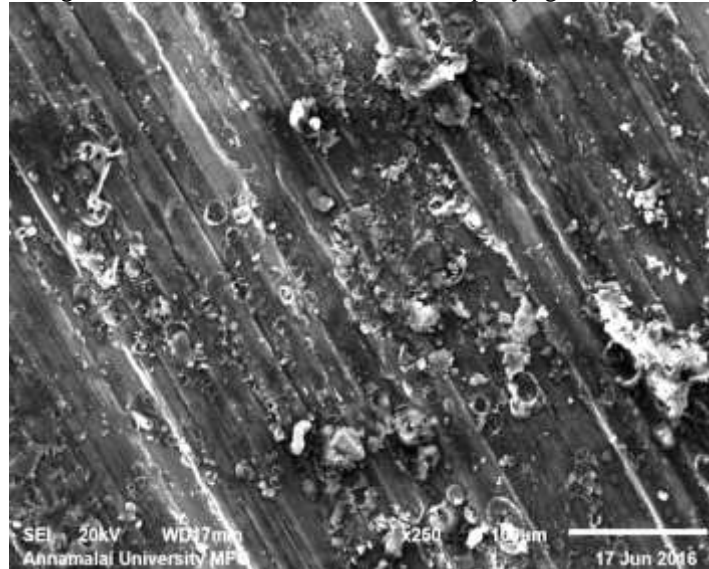


Fig. 5: SEM micrographs showing oxidation at 20 N and 0.3 m/s.

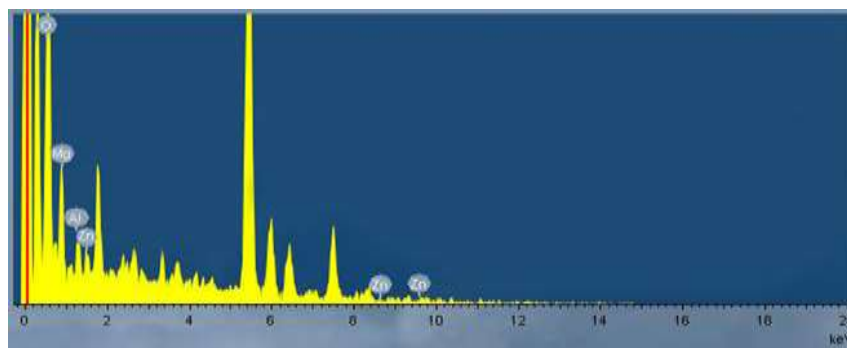


Fig. 6: EDS analysis showing strong oxygen peaks, indicating oxidation of worn surfaces at 20 N and 0.3 m/s.

Fig. 7 shows the SEM image of worn surface at an applied load of 30 N and at a sliding velocity of 0.3 m/s. It was found that delamination wear occurred on the wear surface. The load was increased in the mild wear regime, a gradual transition in the wear behavior of the alloy occurred from an oxidational wear to a delamination wear. In this wear process, the typical wear debris had a shiny metallic appearance and a plate-like shape and the debris was possibly formed as a result of detachment of the sub surface layers from bulk material (delamination wear). The presence of an oxygen peak of low intensity in the EDS spectrum of Fig. 8 implied that the surface of the debris was slightly oxidized, probably when the freshly produced surfaces of the detached particles became in contact with the air. In delamination wear short cracks occur roughly perpendicular to the sliding direction. The intersection of these cracks result in the detachment of sheet-like wear particles, having behind shallow craters. This is well agreed with earlier findings [19]. This is a fatigue-related wear mechanism in which repeated sliding induces subsurface cracks that gradually grow and eventually shear to the surface, forming long thin wear sheets [23]. Das et al. [25] are of the opinion that in delamination wear, the subsurface cracks, which may either, exist earlier or get nucleated due to the stresses, propagate during the course of wear. When such subsurface cracks join the wear surface, delamination is the dominant wear mechanism.

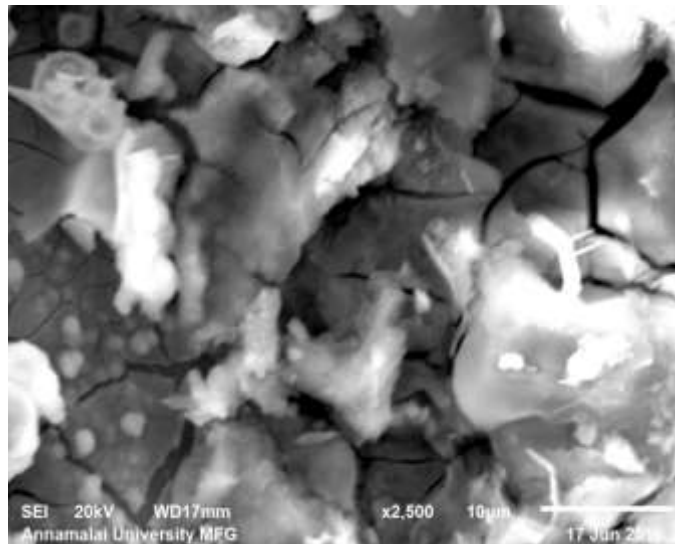


Fig. 7: SEM micrographs showing series of cracks roughly perpendicular to the sliding direction on the pin surface, indicating delamination at 30 N and 0.3 m/s.

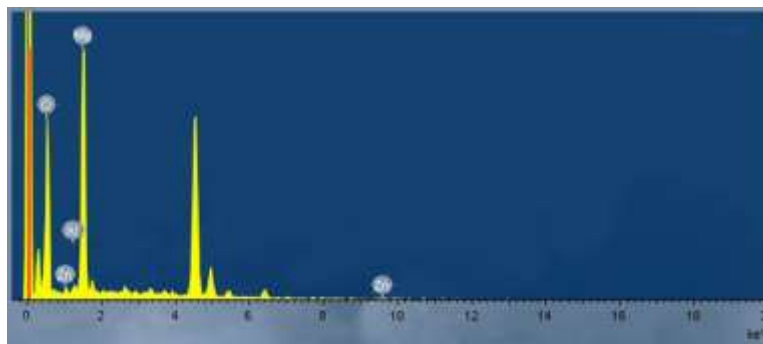


Fig. 8: EDS analysis showing the presence of an oxygen peak of low intensity, indicating the surface is slightly oxidized at 30 N and 0.3 m/s.

Fig. 9 shows the severely of plastic deformation layer at the worn surface tested at 40 N applied load and 0.5 m/s sliding velocity. These features are indicating the occurrence of severe metallic wear. The transition to severe wear accompanied by a significant increase in the roughness of worn surface of AZ31B samples. The severely deformed metallic layers extruded along the sliding direction and out of the contact surface of the sample. Taltavull et al. [26] reported that the main characteristic of the mechanism of plastic deformation is the massive surface deformation and local melting of material, which produce extensive surface damage. Ashok Kumar et al. [27] reported that increase in applied load and sliding velocity resulted in increase in plastic deformation, which resulted in high level of structural disruption and extensive damage for the alloy. The severe plastic deformation leads to higher wear rate with increase in load and speed. Chen and Alpas [22] reported that at higher applied loads the extensive surface damage occurs as a result of plastic deformation of the material layers adjacent to the contact surface. As the temperature increases the yield strength decreases sharply and alloy gets softened. As a result the material becomes prone to easy plastic deformation and they spread out of the contact surface in the direction of sliding as well as by moving sideways.

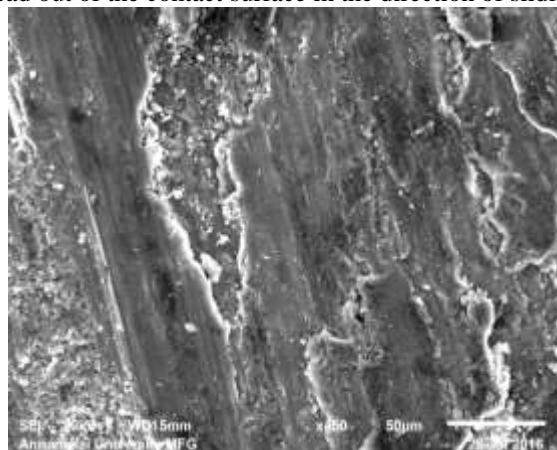


Fig. 9: SEM micrographs showing plastic deformation of worn surfaces at 40 N and 0.5 m/s.

Fig. 10 shows the surface melting of the material tested at 50 N applied load and 0.7 m/s sliding velocity. When the sliding speed and applied load reach certain critical thresholds, flash temperatures at contacting asperities could exceed the melting point of the alloy, thus increasing bulk temperature and causing gradual softening of the alloy. Continued sliding or increases in speed and load would raise temperatures further, leading to melting and rapid increase in wear rate. This is well agreed with Lim et al. [23]. An et al. [24] reported that at higher applied load and sliding velocity conditions surface melting is the dominant wear mechanism for magnesium alloys.

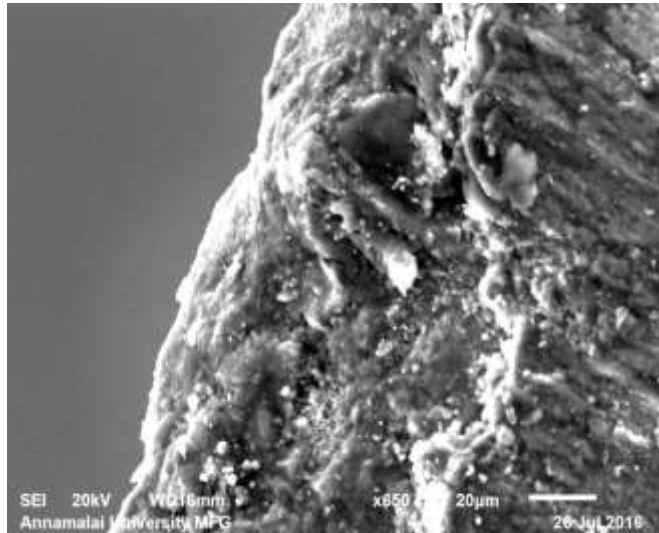


Fig. 10: SEM micrographs showing surface melting of worn surfaces at 50 N and 0.7 m/s.

#### IV. CONCLUSIONS

Pin-on-disc dry sliding wear tests with pins of extruded AZ31B magnesium alloy were investigated against EN32 steel counterface in the applied load range of 10–50 N, sliding velocity range of 0.1–0.9 m/s and at a constant sliding distance of 1000 m. The conclusions of the investigation are as follows:

- The wear rate increases with increase in applied load and sliding velocity.
- When the applied load increases, the wear increases gradually in mild wear regime and the wear increases abruptly beyond certain critical load (transition load). Similar results are observed for varying sliding velocities.
- Five mechanisms are identified during the dry sliding conditions. They are abrasion, oxidation, delamination, plastic deformation and melting.
- At lower applied load and sliding velocity conditions, abrasion, oxidation, delamination are the dominant wear mechanisms.
- At higher applied load and sliding velocity conditions, plastic deformation and melting are the dominant wear mechanisms.
- The wear behavior of the extruded AZ31B magnesium alloy can be controlled by applied load and sliding velocity.

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