

# Wear mechanism map for as-cast AZ31B magnesium alloy

E. Ilanagar, S. Anbuselvan\*

Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar,  
Tamil Nadu -608002, India

## Abstract

*In present work, the wear behaviour of as-cast AZ31B magnesium alloy during dry sliding conditions has been investigated. The experiments were carried out using pin-on-disc type wear apparatus against a steel disc counterface 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 wear mechanism map was drawn. The dominant wear mechanisms were identified in each wear regime. Microstructural characterization results established different mechanisms at different sliding conditions, namely, abrasion, oxidation, delamination, plastic deformation and melting.*

**Key words:** Magnesium alloy; Dry sliding wear; Wear map; Wear mechanism

## 1. Introduction

Magnesium alloys have been largely overshadowed by aluminium alloys for a long time. However, they are becoming one of the important light weight materials in the last few decades. Magnesium alloys maintained a significant usage in machine, aerospace, automotive, space and nuclear energy due to their low densities, high specific buckling resistance, high specific strength, good damping capacities, good manufacturing and recycling capabilities [1]. The wear is a serious problem when magnesium alloys are subjected to sliding motion. The research about the wear of magnesium alloys has received significant attention in recent years. AZ31B magnesium alloy is one of the widely used magnesium alloys and possesses an excellent toughness and ductility [2]. While magnesium alloys would normally not be candidates for bearing, sliding seals or gears, there are situations in which their surfaces could come into contact with other materials so as to make their friction and wear behavior of interest. Moreover, sliding wear is also an important consideration in material processing by rolling, extrusion, forging, etc... from the point of view of understanding the changes in the deformation microstructure at the work-tool interface and the associated heat generation [3]. Thus, the wear behavior of magnesium alloys must be thoroughly investigated.

Nguyen et al. [4] constructed the wear mechanism map for AZ31B magnesium alloy for varying sliding speeds at constant applied load. They analyzed that the microstructural

characterization results established different dominant mechanisms at different sliding speeds, namely, abrasion, delamination, oxidation, adhesion and thermal softening and melting. Taltavull et al. [5] reported the wear mechanism map for AM50B magnesium alloy. The wear testing was measured in a sliding velocity range of 0.1-1 m/s and normal load range of 10-250 N. They concluded that abrasion and oxidation wear mechanisms dominated at lowest sliding velocities and loads. Increasing load and sliding speed led to a combination of oxidation, delamination and adhesion. Also plastic deformation and severe plastic deformation were deducted for the highest applied load and sliding speeds. Taltavull et al. [3] constructed the wear mechanism map for AM60B magnesium alloy. The wear tests were measured in a sliding velocity range of 0.1-1 m/s and using different normal force range of 10-250 N. They concluded that oxidation mechanism dominated at the lowest sliding velocities and loads. Increasing load and sliding speed led to combination of oxidation, delamination and adhesion. At 40 N of load an abrupt change in wear mechanism from delamination to plastic deformation was observed and associated with a mild to severe wear transition. At highest applied load and sliding velocity tested severe plastic deformation was the main wear mechanism. Zafari et al. [6] reported the wear mechanism map for AZ91D magnesium alloy at elevated temperatures. The wear behavior of AZ91 magnesium alloy was investigated under applied loads of 5, 20 and 40 N at the wear testing temperatures of 25 °C to 300 °C. The wear tests were carried out using a pin-on-disk tribometer at a sliding speed of 0.4 m/s for a total sliding distance of 1000 m. They found out the critical contact temperatures at the pin disc interface at which a transition from a mild to a severe wear mechanism might occur. These temperatures were about 140, 180 and 400 °C at the normal loads of 40, 20 and 5 N respectively. López et al. [7] constructed the wear map for ZE41A magnesium alloy. The experiments were carried out in a sliding velocity range of 0.1-1 m/s and normal force range of 5-40 N. They reported the dominant wear mechanisms in different regimes of wear mechanism map.

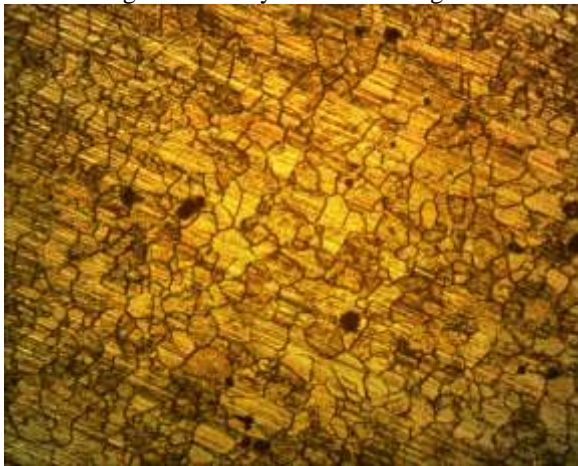
In this present work the wear mechanism map for as-cast AZ31B magnesium alloy was investigated under dry sliding conditions. The transition boundary between mild to severe and

severe to ultra severe wear was analyzed. The dominant wear mechanisms in each wear regime wear identified and interpreted with the wear mechanism map.

## 2. Experimental procedures

### 2.1 Materials

The material studied was as-cast 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 [8]. The initial microstructure of as-cast AZ31B magnesium alloy is shown in Fig. 1.



**Fig. 1. Initial microstructure of as-cast AZ31B magnesium alloy.**

### 2.2 Wear tests

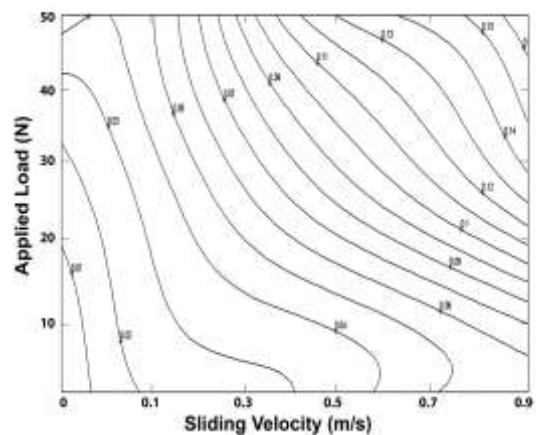
The wear tests were carried out under dry sliding condition in accordance with the ASTM G-99 standard using a pin-on-disc wear testing machine. In the present study, pins of Mg alloys under investigation were machined to 6 mm in diameter and 20 mm in length. The surface preparation procedure of the wear 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 μm 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 μm 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 g/cm<sup>3</sup>). 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.

## 3. Results and discussion

### 3.1 Wear rate map

Wear rate maps are considered one of the best descriptions of tribological conditions and are useful in selecting materials in a wide range of operating conditions. Wear rate maps have been demonstrated to understand the wear characteristics of a given material pair over a range of operating conditions. Once the maps are generated, they allow subsequent analysis in terms of wear transition maps and wear mechanism maps [9]. Fig. 2 shows the wear rate map of as-cast AZ31B magnesium alloy for various dry sliding conditions. This contour wear rate map has been constructed on applied load versus sliding velocity axis using MAT LAB software and wear rate data. Each contour represents the wear rate for different applied load and sliding velocity conditions. The wear rate data are in mm<sup>3</sup>/m x 10<sup>-3</sup>. The wear rate is minimum at lower applied load and velocity conditions and it is maximum at higher applied load and velocity conditions.



**Fig. 2 shows the wear rate map for as-cast AZ31B magnesium alloy for various dry sliding conditions.**

### 3.2 Wear transition map

The availability of the wear transition diagram provides opportunity to study the different wear mechanisms in each region for a material under various sliding conditions. The transition diagram defines the minimum number of wear mechanisms operating in a given system. By examining the contour maps (lines of constant wear rate), lines of equal spacing and lack of curvature usually indicate the same dominant wear mechanism. Valleys and plateaus usually suggest some change in the wear mode. In this way, regions with potentially different wear mechanism can be identified [9]. Fig. 3 shows the wear transition map for AZ31B magnesium alloy. It displays the wear transition boundary as a function of applied load and sliding velocity. The wear rate data is omitted but the emphasis is on the wear mechanism regimes and the transitions between them. It shows three wear regimes as mild wear, severe wear and ultra severe wear. The transition boundary between mild to severe wear and severe to ultra severe wear have been established according to the visual observations of the worn surfaces during the wear tests and not based on a specific wear rate criteria [10].

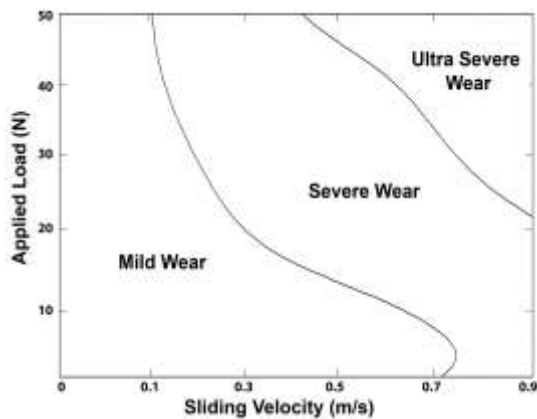


Fig. 3 shows the wear transition map for as-cast AZ31B magnesium alloy.

### 3.3 Wear mechanism map

Wear mechanisms are described by considering complex changes during friction. In general, wear does not take place through a single wear mechanism, so understanding each wear mechanism in each regime of wear becomes important. Wear mechanism maps summarizing data and models for wear, showing how the mechanisms interface, and allowing the dominant mechanisms for any given set of conditions to be identified- could be developed to explore this much broader pattern of wear behavior [11]. Zhang et al. [12] suggested that wear mechanism map can be a

useful tool to predict the conditions under which a tribosystem can operate safely. A wear mechanism map can also serve as a guide line to select wear resistant materials and suitable counterfaces for them. Fig. 4 shows the wear mechanism map for as-cast AZ31B magnesium alloy. Fig. 4(a) shows the abrasion wear tested at 10 N of applied load and 0.1 m/s of sliding velocity. Here presence of fine grooves observed on the worn surface. These grooves occur parallel to the sliding direction. The formation of grooves mainly results from ploughing and cutting of hard particles between the pin and disc [13]. Fig. 4(b) shows the oxidation wear tested at lower applied load of 10 N and at lower sliding velocity of 0.3 m/s, appear dark, while those at higher load and higher velocities retain their metallic luster. This wear mechanism is referred as the oxidation wear [10], in which frictional heating during sliding causes oxidation of the surface, with wear occurring through the removal of oxide fragments. An et al. [14] reported that the thick oxide layer effectively protected the sliding surface resulting in a mild wear condition with accompanying low wear rate. Fig. 4(c) shows the delamination wear at an applied load of 20 N and at a sliding velocity of 0.3 m/s. The load was increased in the mild wear regime, a gradual transition in the wear behavior of the alloy occurred from an oxidation wear to a delamination wear. 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 [8]. In the mild wear regime the wear occurs by abrasion, oxidation and delamination of the bulk material. These wear mechanisms are dominant in mild wear regime. For practical applications this regime can be regarded as the “safe” operation regime since the wear rates are typically low and wear proceeds under the steady- state condition [12]. The severe wear regime is dominated by plastic deformation wear. Fig. 4(d) shows the plastic deformation wear occurred at 30 N applied load and 0.5 m/s sliding velocity. 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. [3] 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. In the severe wear regime plastic deformation induced wear is the dominant wear mechanism. Increase in applied load and sliding velocity causes the local temperature of the contact surfaces exceed the melting temperature of the alloy results gross plastic deformation. In the ultra

severe wear regime surface melting wear is the dominant wear mechanism. Fig 4(e) shows surface melting wear tested at 40 N applied load and 0.7

m/s sliding velocity. Further increase in applied load and sliding velocity causes high contact temperatures between

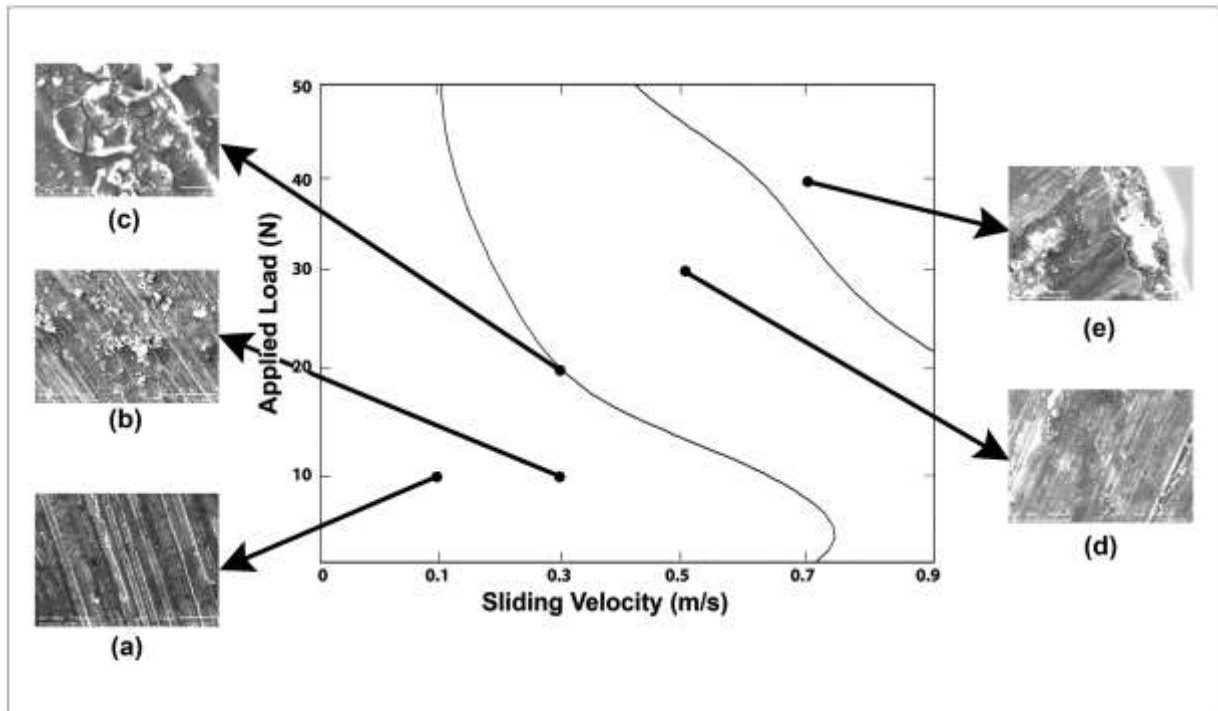


Fig. 4 shows the wear mechanism map for as-cast AZ31B magnesium alloy (c) Abrasion (b) Oxidation Delamination (d) Plastic deformation (e) Melting

pin and disc and also increase in frictional heat which results surface melting. This is well agreed with Lim et al. [15]. An et al. [14] reported that at

higher applied load and sliding velocity conditions surface melting is the dominant wear mechanism for magnesium alloys.

#### 4. Conclusions

Pin-on-disc dry sliding wear tests with pins of 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 is minimum at lower applied load and velocity conditions and it is maximum at higher applied load and velocity conditions. Three wear regimes are found in the wear mechanism map. They are mild wear, severe wear and ultra severe regimes. Abrasion, oxidation and delamination are the dominant wear mechanisms in the mild wear regime. Plastic deformation is the dominant wear

mechanism in the severe wear regime. Melting is the dominant wear mechanism in the ultra severe wear regime.

#### References

1. Chen Dong-feng, Dong Xuan-pu, Zhang Xiong, and Fan Zitian, *Mg alloy surface alloying layer fabricated through evaporative pattern casting technology*, Transactions of Nonferrous Metals Society of China, 2010, vol. 20, pp. 2240-2245.
2. M.N. Mekonen, D. Steglich, J. Bohlen, D. Letzig, and J. Mosler, *Mechanical characterization and constitutive modeling of Mg alloy sheets*, Mater Sci Eng A, 2012, vol. 540, pp. 174–86.
3. C. Taltavull, B. Torres, A.J. Lopez, and J. Rams, *Dry sliding wear behavior of AM60B magnesium alloy*, Wear, 2013, vol. 301, pp. 615-25.
4. Q.B. Nguyenn, Y.H.M. Sim, M.Gupta, and C.Y.H. Lim, *Tribology characteristics of magnesium alloy AZ31B and its composites*, Tribology International, 2015, vol. 82, pp. 464–471
5. C. Taltavull, P. Rodrigo, B. Torres, A.J. Lopez, and J. Rams, *Dry sliding wear behavior of AM50B magnesium alloy*, Materials and Design, 2014, vol. 56, pp. 549–556.

6. A. Zafari, H.M. Ghasemi , and R. Mahmudi, *Tribological behavior of AZ91D magnesium alloy at elevated temperatures*, Wear, 2012, vol. 292–293, pp. 33–40.
7. A.J. López, P. Rodrigo, B. Torres, and J. Rams, *Dry sliding wear behaviour of ZE41A magnesium alloy*, Wear, 2011, vol. 271, pp. 2836– 2844.
8. Q.B. Nguyen, and M. Gupta, *Increasing significantly the failure strain and work of fracture of solidification processed AZ31B using nano-Al<sub>2</sub>O<sub>3</sub> particulates*, J Alloys Compd, 2008, vol. 459, pp. 244-50.
9. S.M. Hsu, and M.C. Shan, *Ceramic wear maps*, Wear, 1996, vol. 200, pp. 154-75.
10. H. Chen, and A.T. Alpas, *Sliding wear map of AZ91 magnesium alloy*, Wear, 2000, vol. 246, pp. 106-16.
11. S.C. Lim, *The relevance of wear–mechanism maps to mild–oxidational wear*, Tribol Int, 2002, vol. 35, pp. 717-23.
12. J. Zhang, and A.T. Alpas, *Transition between mild and severe wear in Aluminium alloys*, Acta Mater, 1997, vol. 45, pp. 513-28.
13. J. Jing, B.I. Guangli, Z. Lei, L.I. Rongguang, L. Jianshe, and J. Zhonghao, *Journal of Rare Earths*, 2015, vol. 33, pp. 77-85.
14. J. An, R.G. Li, Y. Lu, C.M. Chen, Y. Xu and X. Chen, *Dry sliding wear behavior of magnesium alloys*, Wear, 2008, vol. 265, pp. 97–104.
15. C.Y.H. Lim, S.C. Lim and M. Gupta, *Wear behaviour of SiCp-reinforced magnesium matrix composites*, Wear, 2003, vol. 255, pp. 629–37.