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Araştırma / Research

A COMPARISON OF THE DRY SLIDING WEAR BEHAVIOR OF AS-CAST AND HOT ROLLED AZ31B MAGNESIUM ALLOY

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ABSTRACT

Wear resistance is one of the important technological properties of magnesium alloys that may limit their practical applications, though limited information is available in the literature. In this study, wear behavior of as-cast and hot rolled AZ31B magnesium alloy on dry-sliding conditions was investigated using a pin-on disc method. Wear rate was measured at a fixed sliding distance of 1500 m and at different sliding velocities of 0.25, 0.50, 1.00 and 2.00 m/s, as well as different applied loads of 10, 20, 40 and 80 N. Surface morphology of worn surface of the alloy was analyzed using a SEM/EDS. Hot rolled alloy exhibited a better wear resistance than the as-cast alloy due to a finer microstructure and higher hardness. Results showed that ultra-severe plastic deformation was found to be the main wear mechanism at the highest applied load and sliding velocity for the alloy at both metallurgical conditions according to wear maps.

Keywords: Dry sliding wear, AZ31B cast/hot rolled magnesium alloy, wear mechanisms, wear map

DÖKÜM VE HADDELENMİŞ AZ31B MAGNEZYUM ALAŞIMININ KURU ŞARTLARDA AŞINMA DAVRANIŞININ KIYASLANMASI

ÖZ

Aşınma direnci literatürde yeterli bilgi olmaması sebebiyle magnezyum alaşımlarının uygulama alanlarını kısıtlayabilecek önemli teknik özelliklerden biridir. Bu çalışmada pin-on disk yöntemi kullanılarak kuru çalışma şartlarında döküm ve haddelenmiş AZ31B magnezyum alaşımlarının aşınma davranışı incelenmiştir. Aşınma hızı 1500 m sabit kayma mesafesi, 0,25-0,50-1,00 ve 2,00 m/s kayma hızı ve 10-20-40 ve 80 N gibi farklı yüklerde ölçülmüştür. Aşınmış yüzeylerin yüzey morfolojisi SEM cihazı kullanılarak incelenmiştir. Haddelenmiş alaşım ince mikroyapı ve daha yüksek sertlik özelliklerinden dolayı döküm alaşımdan daha iyi aşınma direnci sergilemiştir. Aşınma haritalarına göre sonuçlar en büyük yük ve en yüksek kayma hızında aşırı plastik deformasyonun ana aşınma mekanizması olduğunu göstermiştir.

Anahtar Kelimeler: Kuru aşınma, AZ31B döküm/hadde magnezyum alaşımı, aşınma mekanizmaları, aşınma haritası

1. INTRODUCTION

In last few decades, magnesium and its alloys have been used widely in automotive, aerospace industry and electronic devices such as laptop, tablet and mobile phone owing to their lightweight, high specific strength,

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considerable vibration and shock absorption ability and high recycling potential [1, 2]. Magnesium alloys have also been widely studied as potential materials for temporary medical implants owing to its strength and safe absorbability by the human body, and they have been progressed to some preclinical studies and product commercialization [3, 4]. Among them, Mg–Al are the most common magnesium alloys having superior castability, good corrosion resistance, reasonable mechanical properties and acceptable processing cost [5, 6]. However, their poor resistance to wear, especially in the as-cast condition, limits their extensive application in automotive and aviation industries [7]. Similarly, a good wear resistance is required for load bearing temporary medical implants such as bone screws because friction with the hard cortical bone is unavoidable during the surgical procedure [8]. By subjecting the as-cast alloys to hot deformation like rolling and forging, their hardness and strength are improved, therefore their resistance to friction and wear is improved as well [9-11]. AZ91D is a type of Mg-Al alloys which has been the most commonly used and the most investigated in terms of wear behavior [12-15]. It shows a higher wear resistance than that of AS21 and AM60B alloys against sintered iron alloy [12, 13].

The wear of magnesium is often investigated under dry sliding conditions using a various testing set-up and method. By using a pin-on disc set-up, An et al. [16] found that new Mg-1%Zn-2%Y alloy exhibited good wear resistance compared to AZ91 for applied loads in excess of 80 N. Zhang et al. [17] investigated wear behavior of a series of Mg-Zn-Y alloys against steel with 65 RC hardness as counterface using a block-on wheel system and found that Mg-25Zn-2Y quasicrystal metal had the best wear performance at all applied loads. El-Morsy [18] used a pin-on ring set-up to investigate wear behavior of extruded Mg-6Al-1Zn alloy and identified two main wear regimes: mild wear and sever wear regime. A ball-on disk configuration was used by Chen et al. [19] to study wear behavior of thixoformed and permanent mold cast AZ91 alloy under reciprocating sliding conditions using and revealed that the former was more wear resistance than the latter due to a finer microstructure. Other studies used the pin-on disc configuration to investigate the dry sliding behavior of ZE41A alloy in the as-cast, hot extruded and heat treated conditions [20-22]. They identified three wear regimes: mild, severe and ultra-severe and various wear mechanisms including abrasion, adhesion, oxidation, delamination, thermal softening, melting, plastic deformation, severe plastic deformation.

Other than by alloying and hot deformation, the wear resistance of magnesium alloys has been improved by forming composites. Habibnejad-Korayem et al. [23] found that reinforcement of AZ31 alloy with 2 wt.% Al_2O_3 nano-particles improved wear resistance of the composite due to grain refinement, higher hardness and load bearing capacity. Ding et al. [24] reinforced the same alloy with SiC particles and found the same result.

Our literature survey indicated that the effect of hot rolling on the wear behavior of magnesium alloys is rarely reported. Therefore, in this study dry sliding wear behavior of hot rolled AZ31B alloy was compared with its as-cast state using a pin-on-disc type wear apparatus against a heat treated EN42 steel as the counterface. This method may simulate the condition of a screw insertion into cortical bone when magnesium is used as biodegradable bone screw. A wear mapping approach was taken to represent the wear regimes and the main mechanism of wear in each regime. This study provided new additional knowledge to the field of temporary medical implants especially on the wear behavior of magnesium alloys potentially used as bone screws.

2. MATERIAL AND METHODS

A commercial AZ31B magnesium alloy in as cast billet (diameter of 70 mm) and hot rolled plate (thickness of 12 mm) was used in this work (Magnesium Elektron, England). Chemical composition and mechanical properties of the alloy are given in Table 1.

Table 1. Chemical composition (wt.%) and properties of AZ31B magnesium alloy

Composition	**Mg**	**Al**	**Zn**	**Fe**	**Ni**	**Cu**
AZ31B	Bal.	3.12	1.05	<0.0017	<0.0009	<0.0007

Properties	**Hardness (HV)**	**Tensile strength (MPa)**	**Elongation (%)**
AZ31B as-cast	55 (±5)	168 (±7)	8 (±2)
AZ31B hot rolled	70 (±4)	230 (±6)	20 (±3)

A series of wear tests was performed under a dry sliding condition in accordance with the ASTM G99-95a standard [25] using a pin-on disc wear testing machine (Figure 1). Both the cast and hot rolled AZ31B alloy were machined into pins having a diameter of 6 mm and 10 mm length. The surface of the wear pins was ground manually up to 1200 grit SiC paper, cleaned with acetone and dried in warm air. The counterface was an EN42 steel disc having a diameter of 150 mm and 18 mm thick with a surface roughness (Ra) of 0.1 μm and hardness of HRC 55. The steel disc was cleaned by using an ethanol solution before each wear test.

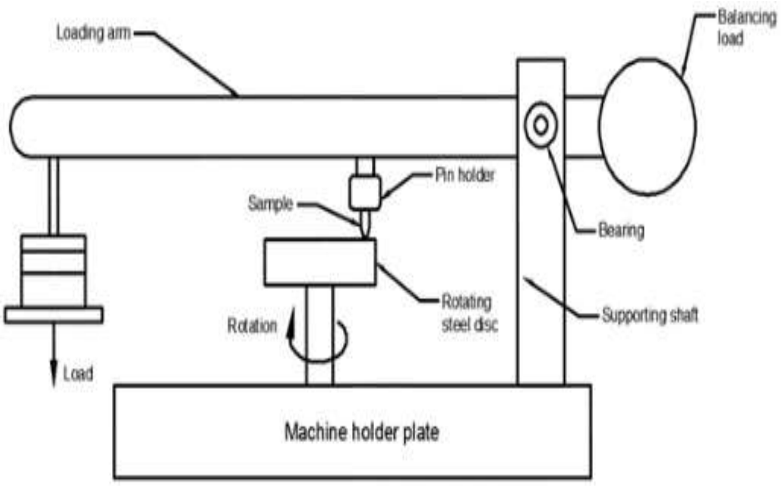

Figure 1. Schematic view of the pin-on-disc machine

The wear tests were performed using sliding velocities of 0.25, 0.50, 1.00 and 2.00 m/s and loads of 10, 20, 40 and 80 N with a constant sliding distance of 1500 m. Mass loss was calculated from the weight difference of the pins measured before and after the test (loose debris was removed). Each test was repeated three times and the average of three tests was considered to determine the wear rate. Volume lost during the wear test was determined from the mass lost using the alloy density to determine the wear rate. To evaluate the wear response of the material under different conditions, the Archard's law was applied [26]:

$$W/L = K\,(F/H) = kF \tag{1}$$

where W is the wear volume, L is the sliding distance, (W/L the wear rate), F is the applied load, H is the hardness of the sample, K is the Archard's constant and k is the specific wear rate.

Hardness of the pins was measured by using an EMCO TEST Duravision 200 machine with a 1 N load using ISO 6507-1 standard [27]. Each hardness value was the average of at least three test results. Microstructure of the samples was viewed via light optical microscope (LOM) with grain size measurement attachment. The pins' worn surfaces were examined by using a Scanning Electron Microscopy equipped with an Energy Dispersive X-ray Spectrometer (SEM/EDS, JEOL JSM-6060 LW, Japan). Metallographic samples were cut using a fine saw without heating and mounted in hardened epoxy resin, ground up to 2000 grit SiC paper, polished with diamond paste of 3 μm particle size, and ultrasonically cleaned in a methanol solution before etching. A mixture of acetic acid (7 mL), picric acid (25 g), ethanol (140 mL), and purified water (40 mL) for 20 s was used to etch and reveal the microstructure. Samples for microstructure evaluation were taken from cross section of both billet and plate.

3. RESULTS AND DISCUSSION

3.1. Microstructure Characterization

Figure 2 presents optical micrographs of the as-cast and hot rolled AZ31B magnesium alloy showing a microstructure consisting of α-Mg phase as matrix and β-$Mg_{17}Al_{12}$ along the grain boundaries as second phase. The hot rolled alloy is characterized by a smaller average grain size (about 18 μm) compared to that of the as-cast alloy (about 53 μm).

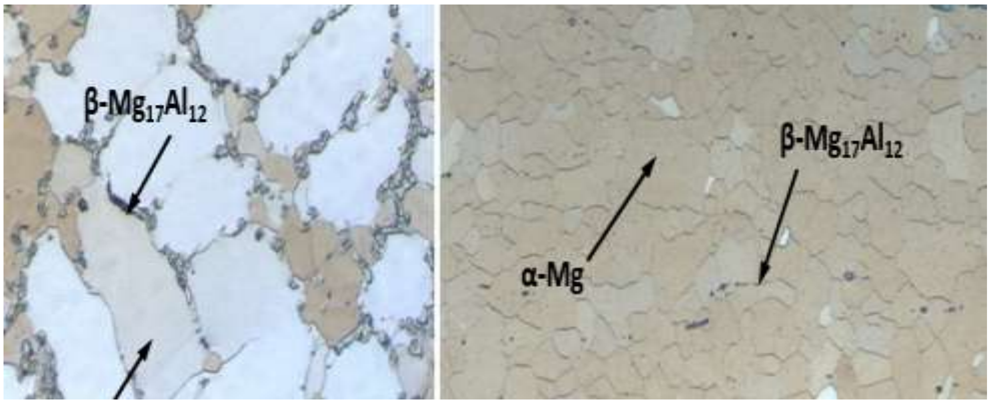

Figure 2. Microstructure of: (a) as-cast, (b) hot rolled AZ31B magnesium alloy

Figure 3 shows volumetric wear rates of the as-cast and hot rolled alloy as the effect of different applied load and at sliding speed. With the increasing sliding velocity (0.25, 0.5, 1.0 and 2.0 m/s), the wear rate going up in function of applied load (Figures. 3a, 3b). A steep slope of wear rate is observed at 20 N for the as-cast alloy and at 40 N for the hot rolled one. This change in slope could be related to the transition of wear regime from mild to severe [13]. Similar behavior is observed where the volumetric wear rate increases as function of sliding velocity with the increase of applied load (10, 20, 40 and 80 N) as shown in Figures. 3b and 3c. A steep slope of wear rate is observed at 0.5 m/s for the as-cast alloy and at 1.0 m/s for the hot rolled one indicating a dominant mild wear regime under the respective sliding velocities.

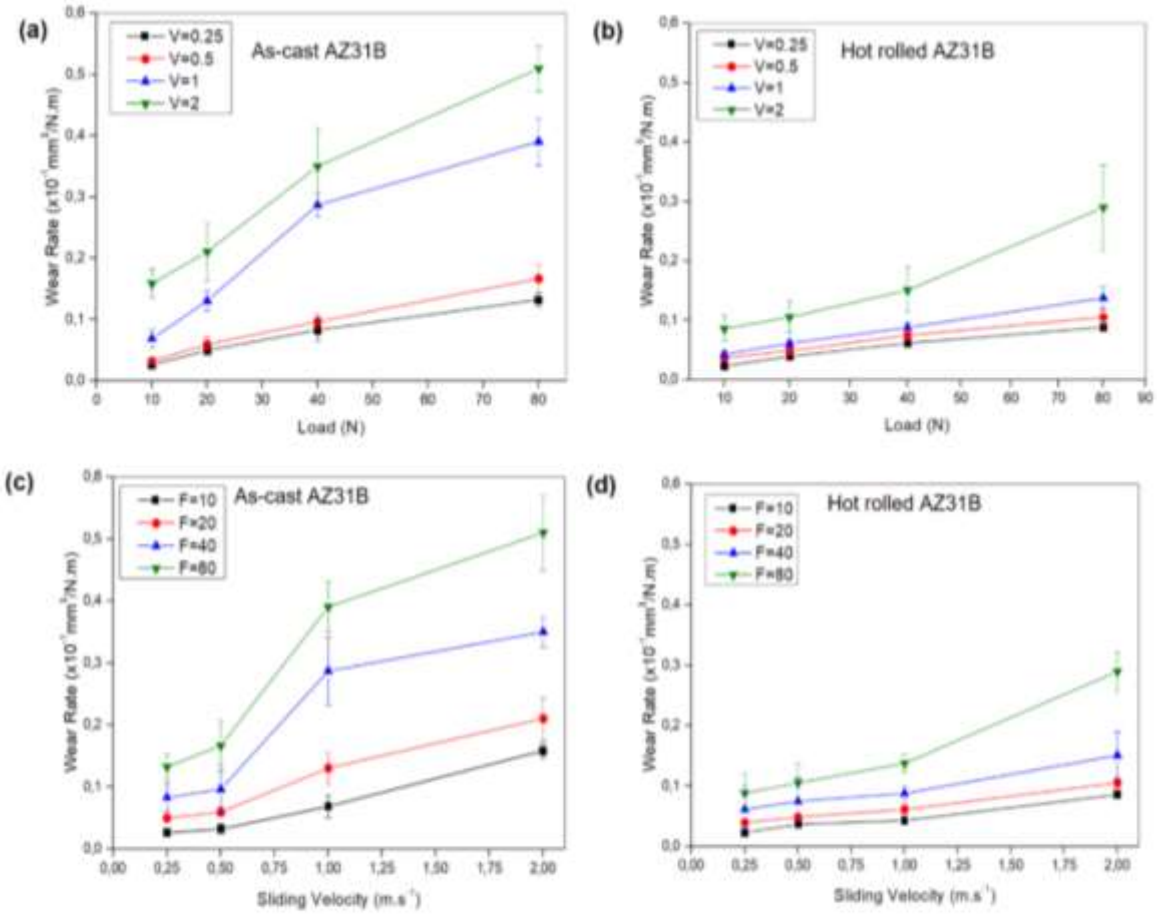

Figure 3. Wear rate of the as-cast and hot rolled AZ31B alloy in function of applied load of (a, b) and in function of sliding velocity (c, d), respectively

The hot rolled AZ31B substrates have average wear rate of $1.17x10^{-2}$ $mm^3/N.m$, $1.83x10^{-2}$ $mm^3/N.m$, $2.14x10^{-2}$ $mm^3/N.m$ and $4.25x10^{-2}$ $mm^3/N.m$, while sliding speeds are 0.25 m/s, 0.50 m/s, 1.00 m/s and 2.00 m/s at 10 N constant load, respectively. On the other hand, average specific wear rates observed for as-cast AZ31B substrates are $1.29x10^{-2}$ $mm^3/N.m$, $1.61x10^{-2}$ $mm^3/N.m$, $3.42x10^{-2}$ $mm^3/N.m$, and $7.93x10^{-2}$ $mm^3/N.m$ as sliding speeds are 0.25 m/s, 0.50 m/s, 1.00 m/s and 2.00 m/s at 10 N constant load, respectively. As seen that, while there is great difference between hot rolled AZ31B substrate specific wear rate and the as-cast AZ31B sample specific wear rate at highest sliding speed, there is no significant difference between the samples at lowest sliding speed. This was also reported in the literature through a study by Anbuselvan and Ramathan [21]. Moreover, it can be concluded that same trend is available at all other loads.

In view of sliding speed point, the average wear rate for the hot rolled AZ31B substrate was $1.14x10^{-2}$ $mm^3/N.m$, $1.97x10^{-2}$ $mm^3/N.m$, $3.07x10^{-2}$ $mm^3/N.m$ and $4.41x10^{-2}$ $mm^3/N.m$, while loads are 10 N, 20 N, 40 N and 80 N at 0.25 m/s constant sliding speed, respectively. However, average specific wear rates observed for as-cast AZ31B substrates are $1.31x10^{-2}$ $mm^3/N.m$, $2.49x10^{-2}$ $mm^3/N.m$, $4.15x10^{-2}$ $mm^3/N.m$, and $6.62x10^{-2}$ $mm^3/N.m$, while same speeds are at 10 N constant load, respectively. Furthermore, it is also seen that same trend is stated at all other speeds.

The results clearly show that the hot rolled alloy had lower wear rate than the as-cast AZ31B alloy at all states of applied load and sliding velocity. The fine microstructure of hot rolled alloy is responsible for its higher hardness, tensile strength and elongation (Table 1). According to Hall-Petch equation, grain size is directly related to mechanical strength, thus also influence hardness. Furthermore, refined grains increase the hardness, hence elevating the wear resistance. Therefore, it is expected to result into higher wear resistance than that of the as-cast alloy as mentioned in earlier works on hot rolled [18, 21, 28] and extruded magnesium alloys [20, 23, 29, 30].

3.2. Wear Mechanism

By observing the worn surface of tested pins under the SEM, the dominant wear mechanism can be identified as abrasion, oxidation, delamination, plastic deformation, and melting.

3.2.1. Abrasion

Figure 4 shows surface morphology of the pins after testing at a constant sliding distance of 1500 m. An abrasion wear took place on the as-cast worn surface subjected to 10 N applied load at 0.25 m/s velocity (Figure 4a), whilst it happened on the hot rolled after subjected to 20 N and 0.25 m/s (Figure 4b), respectively. In both cases the wear surface exhibited a numerous grooves aligned, mostly parallel to the sliding direction which confirmed that abrasive wear mechanism dominated in the tested regime as shown in the previous studies [6, 21, 31].

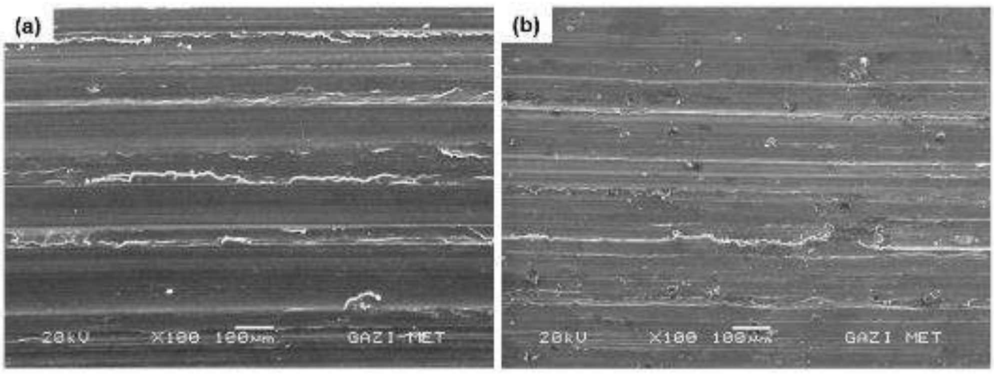

Figure 4. SEM images of the worn surfaces of: (a) as-cast alloy at 10 N and 0.25 m/s, (b) hot rolled alloy at 20 N and 0.25 m/s, showing grooves and scratches as sign of abrasion

3.2.2. Oxidation and Delamination

Figures 5a and 5b show SEM micrographs of worn surfaces of the as-cast alloy and the hot rolled one after subjected to applied load and sliding velocity of 10 N and 0.5 m/s and of 20 N and 0.5 m/s, respectively. Magnesium alloys are known to have a strong tendency to oxidation, which plays a significant role in the wear behavior [32]. The worn surfaces were covered broadly by a thin layer of fine particles composed by magnesium oxide indicated by the strong peaks of oxygen in the EDS spectra. The heat generated from friction during sliding leads to the formation of this oxide layer which was then removed as debris or fragment due to the repeated sliding. The debris fills in the valleys on the pin surface and is compacted to form a protective layer, thus prevents a metallic contact between the magnesium alloy pin and the steel disc resulting into a minimum absolute wear rate. Selvan and Ramanathan [11] reported that a thick oxide layer effectively protects the sliding surface resulting in a mild wear condition with accompanying low wear rate.

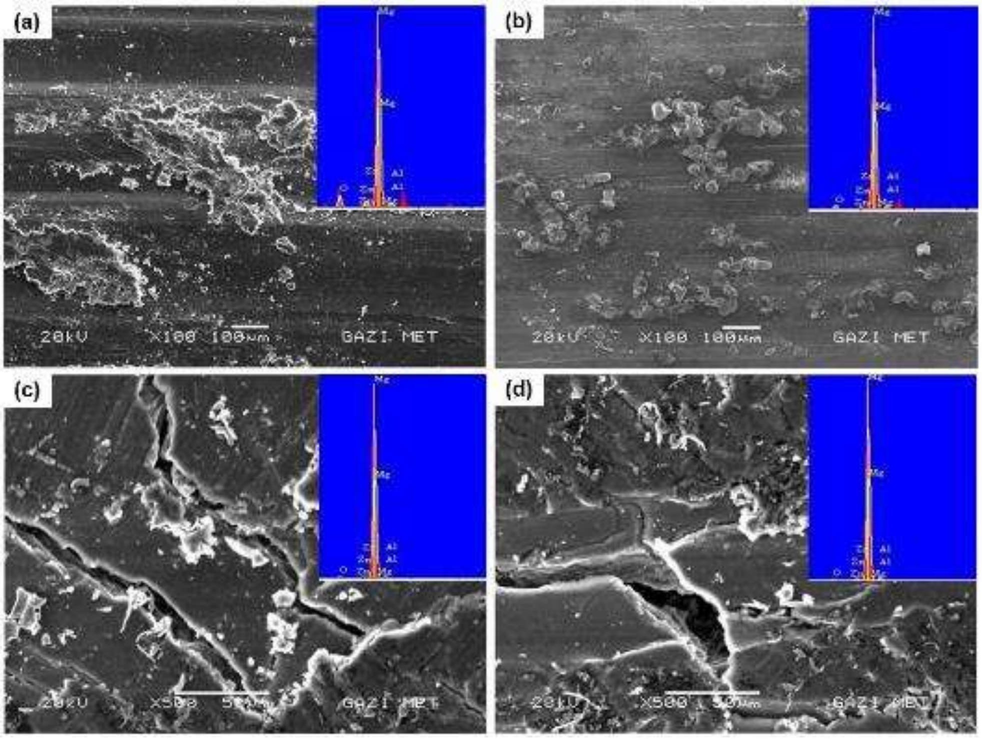

Figure 5. SEM micrographs of the worn surface of: (a) as-cast alloy at 10 N and 0.5 m/s, (b) hot rolled alloy at 20 N and 0.5 m/s showing a sign of oxidation, (c) as-cast alloy at 20 N and 0.5 m/s, (d) hot rolled alloy at 40 N and 0.5 m/s showing cracks and delamination. Inset: EDS spectra of the particles.

Figures 5c and 5d show SEM micrographs of the as-cast alloy at 20 N and 0.5 m/s and the hot rolled one at 40 N and 0.5 m/s, respectively. It indicates a delamination, a wear mechanism characterized by a detachment of material due to formation of cracks perpendicular to the sliding direction. The worn surface experience a hardening even at a low loading [6] and when the applied load increases, a systematic transition in the wear behavior occurs from an oxidational wear to a delamination wear [16]. The presence of oxygen peaks at low intensity in the EDS spectra indicates that the surface was slightly oxidized when the newly produced surface of the detached particles became in contact with the air. In delamination wear, short cracks occur coarsely perpendicular to the sliding direction. The intersection of these cracks results in the detachment of sheet-like wear particles with the size of crack voids is approximately 20-70 µm long and 15-30 µm deep, depending on the material. The subsurface cracks, which may either exist earlier or get nucleated due to the stresses, propagate during the course of wear and cause delamination as the main wear mechanism [33]. Similar findings are reported in the earlier works [6, 14, 33].

3.2.3. Plastic Deformation and Melting

Figures 6a and 6b show a plastically deformed worn surface of both as-cast and hot rolled alloy pins. Plastic deformation is a serious wear mechanism characterized by large surface deformation without crack. This wear mechanism introduces an extensive surface damage leading to a higher wear rate with increasing load and speed. Venkataraman and Sundarajan [34] stated that the transition from delamination to plastic deformation happens with increase in loads and speeds. It was reported that increase in applied load and sliding velocity results into the rise in plastic deformation [35]. The deformed surface layer extended along the sliding direction and out of the contact surface of the pin resulting into a transition from mild to severe wear accompanied by the increase in surface roughness [36]. As the friction gives a rise to temperature, the alloy softens and consequently becomes easily deformed and spread out of the contact surface in the direction of sliding as well as by moving sideways [35].

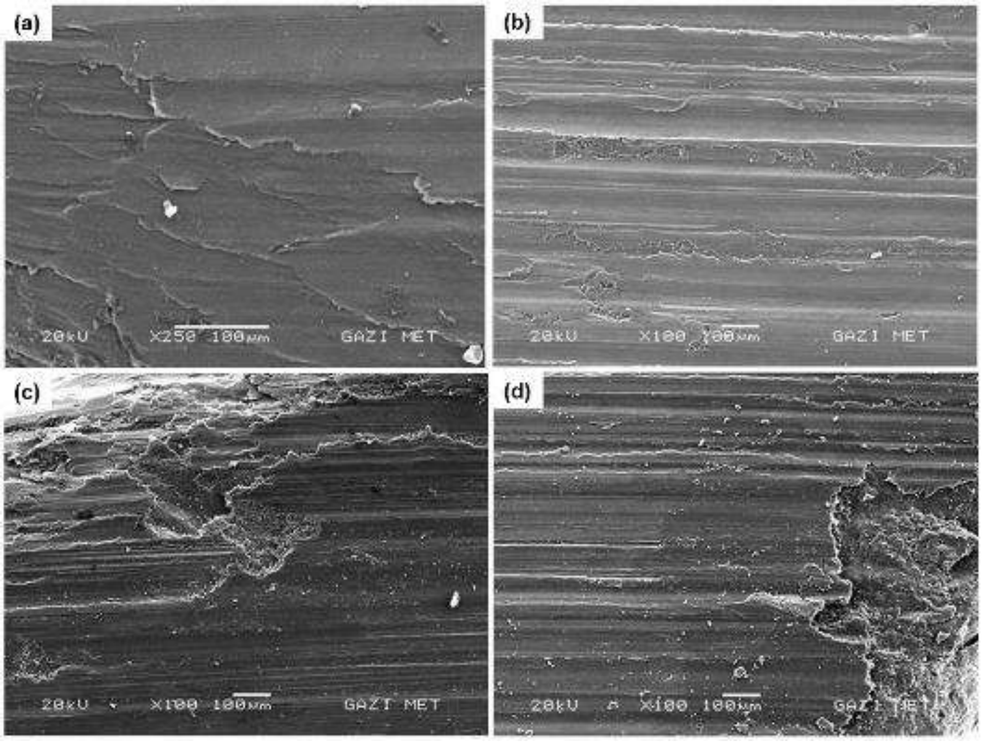

Figure 6. SEM micrographs of the worn surface of: (a) as-cast alloy at 20 N and 1 m/s, (b) hot rolled alloy at 40 N and 1 m/s showing a sign of plastic deformation, (c) as-cast alloy at 40 N and 2 m/s; (b) hot rolled alloy at 80 N and 2 m/s showing a sign of melting

Figures 6c and 6d show SEM micrographs of worn surface of as-cast alloy tested at 40 N and 2.0 m/s and hot rolled one tested at 80 N and 2.0 m/s, respectively showing a sign of surface melting. As the applied load and sliding speed increased above the crucial threshold limit value, the localized temperature at contacting surfaces could exceed the melting point of the alloy [37]. According to Zafari et al. [38] and Huang et al. [39], during a wear test at the highest applied loads, i.e. above 40 N or 50 N, the local temperature of the contact surfaces exceeded the melting point of magnesium alloy (650 ^{o}C) resulting into a friction-induced surface melting. The molten metal spread out of the contact surface in the sliding direction as well as by moving sideways. During the sliding wear, the solidified material formed thin layers. The new layers are continuously generated over the previously formed layers.

3.3. Wear Maps

Figure 7 illustrates a mapping of wear rate and wear mechanism of the as-cast and hot rolled AZ31B magnesium alloy for different dry sliding condition. The maps plot wear rate (in $mm^3/m\times10^{-1}$) and wear mechanism over sliding velocity versus applied load using the ORIGIN software. Each contour shows the wear rate for different sliding velocity and applied load conditions. Wear rate mapping is useful for completely understand the wear behavior of an investigated material over a range of testing condition [40], in this case for finding the boundary of sliding velocity and applied load which results into certain wear rate. From the contour maps, lines of equal spacing and lack of curvature usually mean the same dominant mechanism. Recesses and ledges on the map generally recommend some changes in the wear type. Hence, regions with potentially different wear mechanism can be defined. Wear mechanism mapping help to select wear resistance materials and their suitable counterfaces. Zhang and Alpas [36] recommended that wear mechanism mapping could be a helpful instrument to forecast the wear conditions. The wear mechanism mapping describes material behavior toward wear separated by a transition line which is function of two or more process parameters. Wear transitions could be described as the rapid increasing in wear rate over a small change in conditions such as load, speed, temperature or time. Wear transition plots provide opportunity to examine the different wear mechanisms in each region for investigated materials under various wear parameters.

Three wear regimes are obtained as mild, severe and ultra-severe wear for both as-cast and hot rolled alloys. In the mild wear regime, the wear takes place by abrasion, oxidation and delamination of the bulk material. These wear mechanisms are dominant in the mild wear regime. For industrial applications, the mild wear regime could be considered as a "safe" operation regime because the wear rates are typically low and wear proceeds under steady-state condition [36]. Plastic deformation based wear is the dominant wear mechanism in the severe wear regime. An increase in sliding velocity and applied load leads to the rise of local temperature at contact surfaces of the alloy leading to a great plastic deformation. The transition from mild to severe wear occurs with the changes in sliding velocity and applied load. Surface melting is the dominant wear mechanism in the ultra-severe wear regime. Further increase in sliding velocity and applied load leads to a higher contact temperature between the pin and the steel disc and also gives rise to the frictional heat which concludes a surface melting. The transition from severe wear to ultra-severe wear is also checked by sliding velocity and applied load giving a broader safe operating regime for hot rolled alloy than the as-cast one.

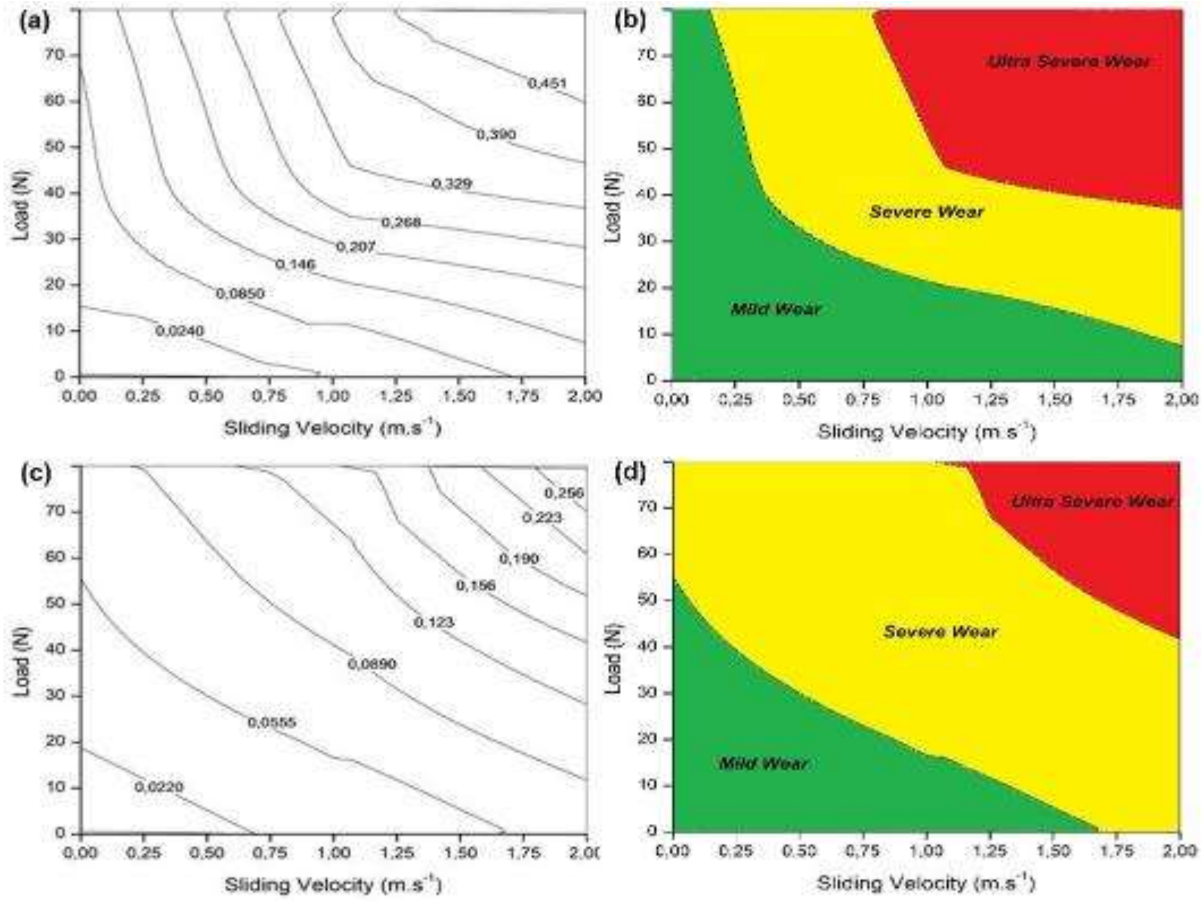

Figure 7. Maps of wear rate and wear mechanism of: (a, b) as-cast, (c, d) hot rolled AZ31B alloy

4. CONCLUSIONS

Wear behavior of the as-cast and hot rolled AZ31B magnesium alloy was studied using a pin on disc method in a range of applied load from 10 to 80 N at various sliding speeds of 0.25, 0.50, 1.00 and 2.00 m/s. Results shows that the wear rate increases with increasing sliding velocity and applied load for AZ31B magnesium alloy in both as-cast and hot rolled conditions. The alloy experience five main wear mechanisms which are abrasion, oxidation, delamination, plastic deformation and melting. The hot rolled alloy exhibits a better wear resistance compared to as-cast state due to its higher hardness and strength as the consequent of its finer grains. The observation on the wear surfaces reveals three wear regimes: mild, severe and ultra-severe wear. Based on wear measurement and observation, maps of wear rate and wear mechanism for the alloy in both conditions were constructed and give guidance in determining a safe wear regime in function of applied load and sliding velocity.

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