Study on the Fretting Wear Properties of Cast and Extruded AZ31 Magnesium Alloy

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Abstract

The study on magnesium alloy fretting wears mainly focuses on micromotion at low frequencies in the scale of a few Hz to tens of Hz. However, limited studies have focused on fretting wear behavior under high-frequency conditions. The friction coefficient and wear mechanism of the fretting wear of cast and extruded AZ31 magnesium alloy were tested and studied at different loads and frequencies under dry friction and lubrication conditions in this paper. Results show that the friction coefficients of cast and extruded AZ31 magnesium alloys increased with load under dry friction conditions. The friction coefficients first increased and then decreased with the increase in frequency. The main damage mechanisms of the cast and extruded AZ31 magnesium alloys fretting wear changed from abrasive to adhesive wear with the increase in load and frequency. Under lubrication condition, only slight abrasive wear and tiny spalling were observed on the worn surface. Both the friction coefficient and the wear amount show a trend of increasing greatly due to the oil lack of friction interface when the frequency is greater than 100Hz. These results provide reference for magnesium alloy friction mechanism and application in high speed.

Keywords

AZ31 Magnesium Alloy; High Frequency; Fretting Wear; Lubrication; Wear Mechanism.

1. Introduction

Fretting wear damage exists on tightly mating parts subjected to quasi static loading rounder condition with small amplitude oscillating movement between two contacting surfaces[1], which causes failure of components and parts. Considering that the fretting wear damage is elusive, early damage is hard to detect, and it easily causes disastrous consequences. Fretting wear is a great challenge in the industry[2]. Mechanism of fretting is very intricate, and it involves various mechanisms such as adhesive, abrasive, oxidative and fatigue-induced wear[3].

Considering the light weight of the equipment, light metal materials such as aluminum alloy and magnesium alloy are gradually applied in a large number of structural components such as rail transit and aircraft. These components operate under high-frequency vibration conditions, which can reach hundreds of Hertz. After a long time of work, fretting wear and interface corrosion easily occur[4-6]. Considering that magnesium alloys are widely used, fretting wear becomes increasingly serious[7-9]. The fretting wear properties of magnesium alloys are mainly studied by casting AZ91D and AM60B magnesium alloys and deformed ZK60, AZ31, and Mg-Li-Al magnesium alloys. With the increase of test temperature (20–300 °C), the wear volume of friction pair decreases first and then increases, and the oxidation degree of wear surface decreases at 2.5 Hz [10]. Mg–Li–Al magnesium alloy has lower friction coefficient and wear volume, and adhesion and peeling are the main wear mechanisms under low displacement amplitude. When the displacement amplitude increases to 200 μm, abrasive wear and oxidation wear are the main wear mechanisms with varying number of oscillation frequency (1–9 Hz)[11]. With the increase in oscillation frequency (>6 Hz), Mg–Li–Al magnesium alloy shows decrease in COF caused by the formation of third body (oxide layer). The fretting tests on AZ91D and AM60B magnesium alloys at the amplitude of 0.5–10 Hz show that different fretting wear regions correspond to different wear mechanisms, and the main components of the wear debris are metal debris and oxides[12-14]. The wear mechanisms of AZ91 magnesium alloy are oxidation wear and fatigue spalling, and that of micro-arc oxidation coating is mixed abrasive wear and fatigue spalling[15]. These studies underline the strong dependence of wear mechanism in magnesium alloys on various parameters such as load, amplitude, and frequency. However, the current studies on the fretting wear of magnesium alloys mainly focus on the fretting at low frequencies in the scale of several Hertz to tens of Hertz. Limited studies have focused on fretting wear behavior at high frequencies.

The further application of magnesium alloy in high-end equipment needs the support of a large number of fretting wear performance analysis results under high-frequency vibration conditions. In practical application, corrosion and fretting wear performance can be reduced by adding an anti-corrosion lubricant or fretting wear lubricant to the connection position. Therefore, the fretting wear law and wear mechanism of cast and extruded AZ31 magnesium alloys under different loads, different frequencies and with the addition of lubricant to the interface are studied in this paper. It provides reference for the application of magnesium alloy in extreme working conditions such as high temperature and speed in large-scale, high-end equipment such as rail transit and aircraft..

2. Experimental Method

2.1 Experimental Materials

The cast AZ31 magnesium alloy ingot was homogenized at 400 °C for 7 h, and the pre-heating temperature of the mold was 375–380 °C. The alloy was extruded from the original diameter of 120 mm to a bar diameter of 30 mm at 400 °C with the extrusion speed of 5 mm/s. The chemical constituents of the cast and extruded magnesium alloy and the friction pair of GCrl5 steel balls are shown in Table 1. The tensile strength of cast AZ31 magnesium alloy is approximately 200 MPa, the tensile strength after extrusion is approximately 270 MPa, and the tensile strength of GCrl5 is approximately 860 MPa. Kluber 14–141 grease is selected as the lubricant.

Table 1. Primary chemical constituents of AZ31 magnesium alloy and GCr15 steel ball

Materials	Mg	Al	Zn	Mn	Ni	Fe	Si	Cr	V
AZ31	95.8	3.1	0.8	0.3	-	-	-	-	-
GCr15		-	-	0.3	0.2	97.6	0.25	1.5	0.15

2.2 Test Equipment

SRV V was selected as the test equipment for fretting wear. The principle is shown in Figure 1. The operating conditions of the equipment are loading range of 0–1, 200 N, amplitude range of 0–4 mm, frequency range of 10–500 Hz, reciprocating form of motion is, and temperature range of room temperature to 300 °C. A tribological test was tested by ball/plane contact.

The AZ31 magnesium alloy sample is a cylindrical block with a diameter of 24 mm and a height of 12 mm with a surface roughness of 0.02 μm. The surface roughness of the GCrl5 steel ball with a diameter of 10 mm is approximately 0.02 μm. Three-dimensional white light interferometer was used to observe the three-dimensional wear morphology of the worn surface and calculate the wear volume. Scanning electron microscope (SEM) was used to analyze the wear morphology of the worn surface.

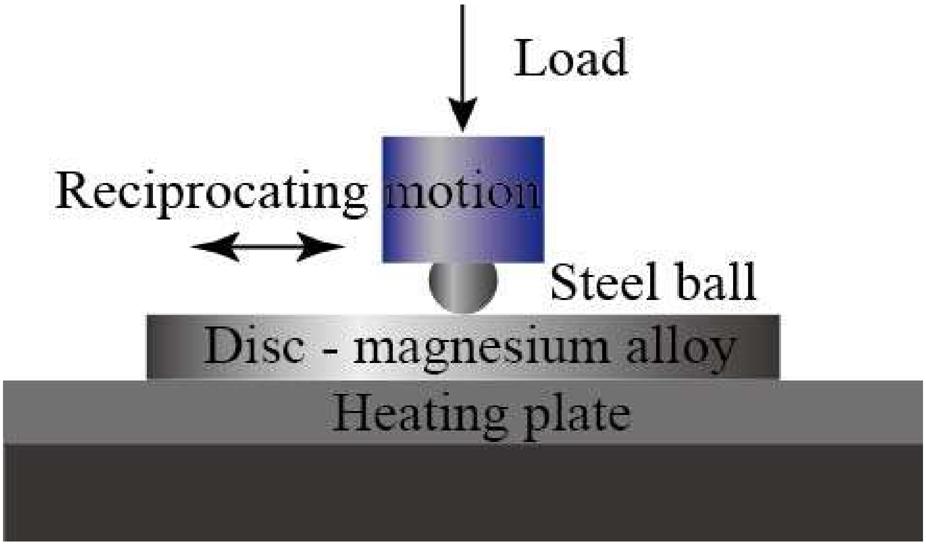

Figure 1. Schematic diagram of the tribological test rig

2.3 Fretting Wear Test Parameters

The effects of different loads (2–100 N) and frequencies (10–300 Hz) on the friction coefficient and wear quantity and fretting wear mechanism of cast and extruded AZ31 magnesium alloys were studied under the conditions of 50 °C, amplitude of 80 μm, and grease lubrication for 30,000 times. The specific test scheme is shown in Table 2.

Table 2. Fretting wear test scheme

Projects	Parameters					Notes
Sample	Cast/extruded deformation					
Lubrication medium	With/without					
Temperature(°C)	50					
Load(N)	2	10	20	50	100	Frequency 50 Hz
Frequency(Hz)	100	500	100	200	300	Load 20 N
Amplitude(μm)	80					
Number of cycles(time)	30000					

3. Results and Discussions

3.1 Microstructure

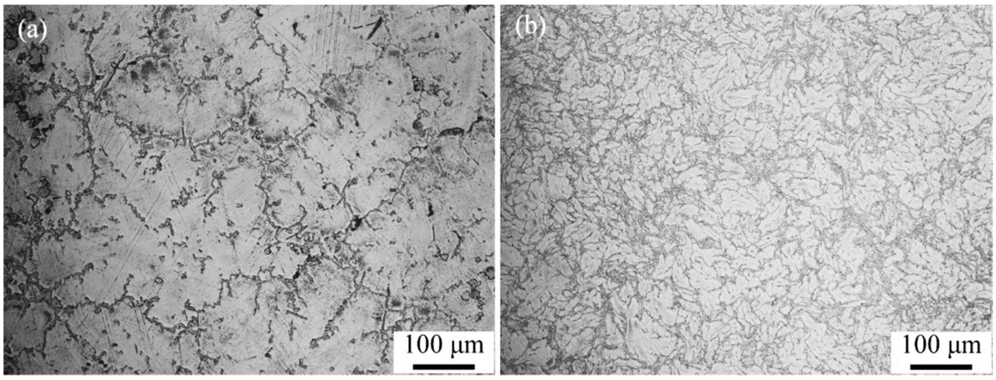

Figure 2. Metallographic microstructure of cast (a) and extruded (b) AZ31 magnesium alloy

The metallographic microstructures of cast and extruded AZ31 magnesium alloy are shown in Figure 2. The microstructure of cast magnesium alloy shows obvious non-equilibrium solidification characteristics with non-uniform grain size and numerous dendritic crystals. The average grain size is approximately 100 μm. Dynamic recrystallization occurs during extrusion, and the grains are refined obviously. Its diameter changes from 100 μm cast to 10 μm. The microstructure of the magnesium alloy is effectively refined by extrusion deformation, and the composition segregation is improved in as-cast state.

3.2 Effects of the Load and Frequency on the Friction Coefficient

The typical friction coefficient curves of cast and extruded AZ31 magnesium alloys under dry friction and grease lubrication are shown in Figure 3. The test conditions are load of 2 N, frequency of 50 Hz, amplitude of 80 μm, and stroke of 9.6 m. The friction coefficients of cast and extruded samples are relatively stable with the increase of friction stroke. Under dry friction, the friction coefficient fluctuates slightly. Especially for extruded alloy, the relative fluctuation range is large under dry friction condition. Under lubrication condition, the friction coefficient curve is relatively smooth and steady.4

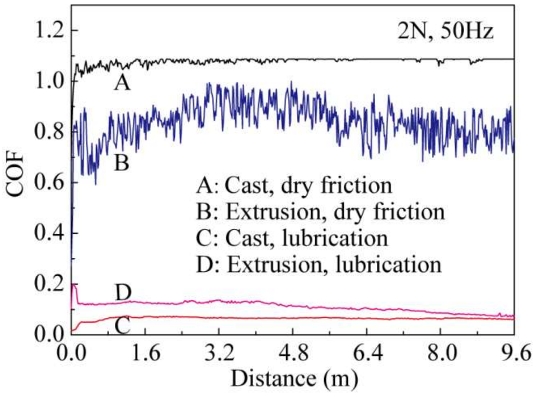

Figure 3. Typical friction coefficient curves

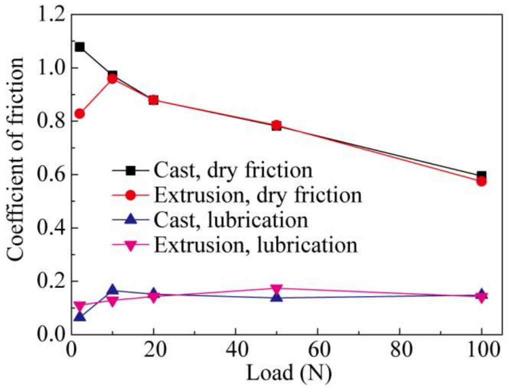

Figure 4. Friction coefficient values under different loading conditions

The friction coefficients of cast and extruded AZ31 magnesium alloys decrease with the increase of load under dry friction condition. Under the same test conditions, a slight difference was observed in the friction coefficient between the two states, as shown in Figure 4. This phenomenon may be caused by the increase in actual contact area and interface friction temperature with the increase in load. The high interfacial temperature decreased the interfacial adhesion and friction coefficient. The friction coefficients of cast and extruded alloys in lubricating medium slightly changed with the increase of load. The frictional coefficients of fretting wear of cast and extruded magnesium alloys under lubrication (e.g., the frictional coefficients are approximately 0.13 and 0.14 when the load is 20 N) are lower than the corresponding frictional coefficients under dry friction (the frictional coefficients are about 0.86 and 0.80 when the load is 20 N). The increase in load only slightly affected the friction coefficient under lubrication condition.

Under dry friction, the friction coefficients of cast and extruded AZ31 magnesium alloys fluctuated between 0.6–0.8 with the increase of frequency, as shown in Figure 5. The friction coefficients of cast and extruded samples increased slightly with the increase in load in the lubricating medium. The friction coefficients of cast and extruded magnesium alloys in lubrication state (e.g., the friction coefficients are approximately 0.20 and 0.24 when the frequency is 100 Hz, respectively) are less than the corresponding friction coefficients of dry friction (approximately 0.74 and 0.73 when the frequency is 100 Hz). Under the lubrication condition, the friction coefficient increases gradually with the increase of frequency.

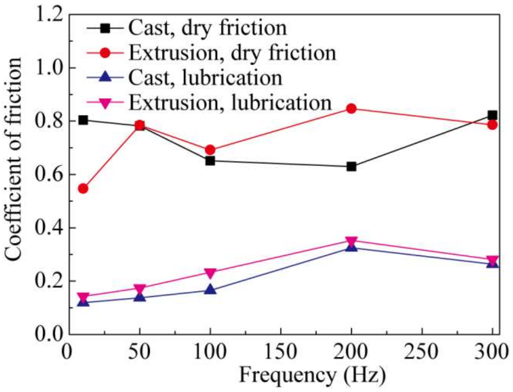

Figure 5. Friction coefficient values at different frequencies

3.3 Effects of Load and Frequency on

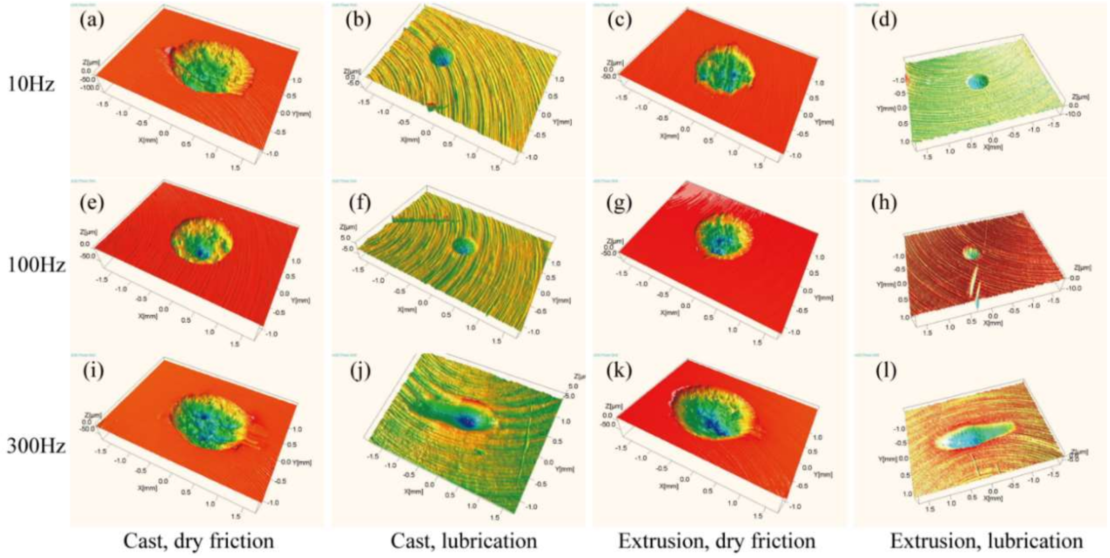

Figure 6. Three-dimensional morphological characteristics of wear under different loads and frequencies (load 20N)

The wear size of cast and extruded AZ31 magnesium alloys tends to increase as the frequency increases, as shown in Figure 6. The wear size decreased under lubrication. When the frequency is 300 Hz, the grinding crack appeared oval, especially in the lubrication state, where it easily appears. The existence of lubricating medium increases the motion amplitude in the high-frequency reciprocating process. The size of grinding crack increases with the increase of load and frequency, as shown in Figure 7. With interfacial lubrication, the size of grinding crack is obviously reduced. In the cast condition, the edge of the grinding crack is slightly raised by the reciprocating extrusion deformation.

Under the condition of dry friction, the wear volume of cast and extruded AZ31 magnesium alloy increased first and then decreased with the increase in load, as shown in Figure 8. The wear volume of extruded alloy is higher than that of as-cast alloy when the load is greater than 10 N. The wear volumes of the as-cast and extruded magnesium alloy samples increased slightly with the increase in load, and only a slight difference was observed between the cast and extruded magnesium alloy samples. Under the same conditions, the fretting wear volumes of as-cast and extruded alloy samples under lubrication are smaller than those under dry friction. Under lubrication condition, the increase in load slightly affected the wear volume.

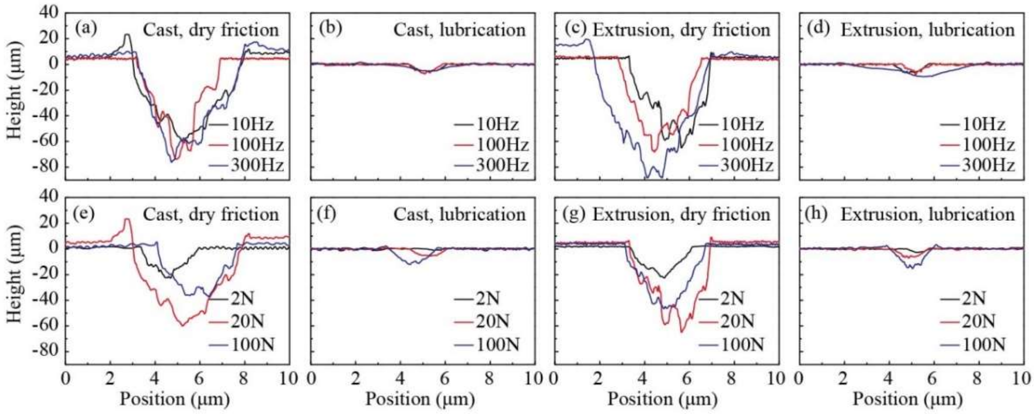

Figure 7. Morphological features of the cross-section of wear

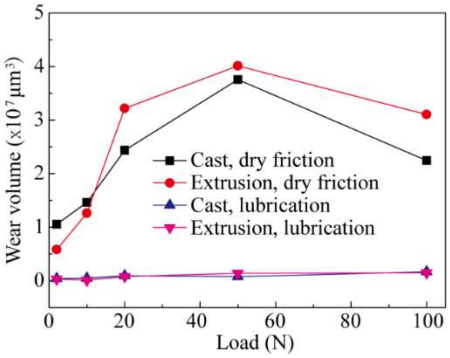

Figure 8. Change in wear volume under different loading conditions

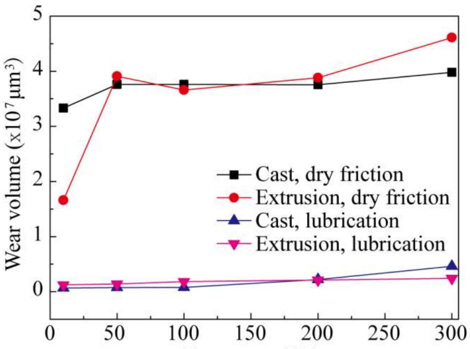

Figure 9. Change in wear volume under different frequency conditions

The wear volume of the cast and extruded AZ31 magnesium alloy increased with the increase in frequency under dry friction conditions, as shown in Figure 9. The wear volume of the cast and extruded magnesium alloy increased slightly with the increase in load under lubrication conditions, but the degree of growth is small. Under lubrication conditions, the wear volume of fretting wear in lubrication state is smaller than the corresponding friction coefficient of dry friction.

3.4 Wear Morphology and Wear

The SEM morphologies of grinding crack under different load conditions are shown in Figures 10 and 11. The area of grinding crack increased, and the fretting damage was aggravated by the increase in load (Figure 10). When the load was 2 N, the debris covered the whole contact area. With the increase in load, the debris gradually accumulated towards the center and edge of the wear mark. When the load was 50 N, the debris accumulated at the edge and center of the wear mark. The SEM morphology of the wear marks after dry friction fretting test of the extruded AZ31 magnesium alloy shows that the debris cover the entire contact area under low load (Figure 11). With the increase in load, the debris gradually accumulated towards the center and edge of the wear mark. The results show that the wear center of cast and extruded magnesium alloy is mainly adhesion, and the wear edge is mainly abrasive wear under different load states. Moreover, the number of abrasive particles on the wear surface of the extruded magnesium alloy is less than that of the corresponding casting sample.

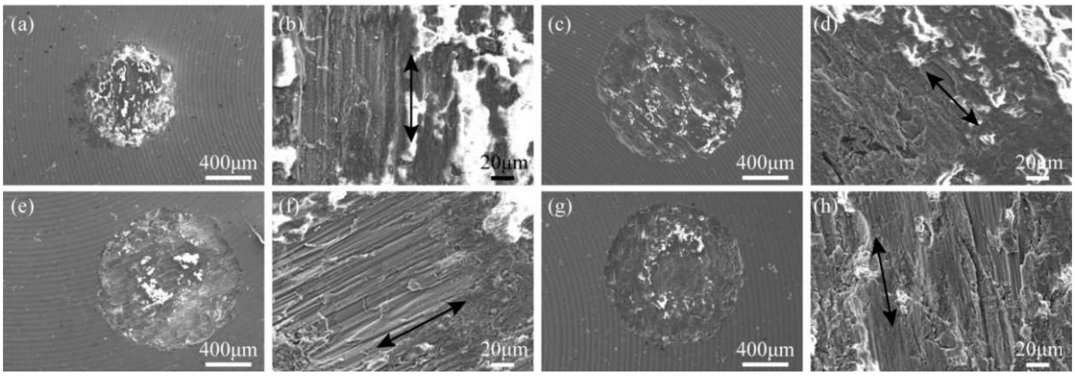

Figure 10. Dry friction wear morphology of as-cast AZ31 magnesium alloy under different loading conditions, (a) and (b) 2N, (c) and (d) 20N, (e) and (f) 50N, (g) and (h) 100N, frequency 50Hz

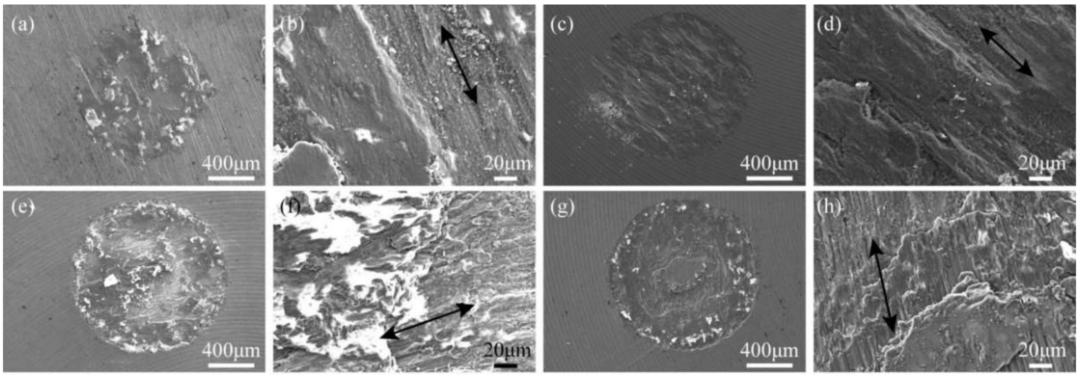

Figure 11. Dry friction wear morphology of extruded AZ31 magnesium alloy under different loading conditions, (a) and (b) 2N, (c) and (d) 20N, (e) and (f) 50N, (g) and (h) 100N, frequency 50Hz

When two friction pairs of surfaces are brought into contact, they are originally separated by oxide layer. Initially, the oxide layer is dispersed, followed by metal transfer with increasing slip. The rupture of AZ31 magnesium alloy junctions during oscillatory motion leads to the formation of debris.

The oxidation of debris can occur initially on the surface itself or during its formation during fretting. The formation of the debris layer can decrease coefficient of friction as the debris can 'roll' between the contacts. Steady state is achieved, because mild wear persists at increased loads because of the abrasive action of the 'rolling debris' on the AZ31 magnesium alloy surfaces[1].

Based on Figures 10 (c) and (d), 11 (c) and (d), and 12, at low frequencies, the abrasive particles of casting and extruded deformation samples cover the entire wear mark area. With the increase in frequency, the abrasive quantity on the surface gradually decreased. At high frequency of 300 Hz, a lot of cracks appeared on the surface of the debris layer, which fell off in chunks and displaced the surface of the wear mark. The surface of magnesium alloy exhibited adhesive wear and lamellar peeling at different frequencies. At high frequency (300 Hz), the large debris on the surface of the wear marks showed spalling of large debris under the action of shear force. Therefore, the adhesion wear of AZ31 magnesium alloy is more significant at high frequency. The number of abrasive particles in the extruded samples is obviously less than that in the cast samples, and this phenomenon was mainly caused by adhesion wear. Casting mainly involves abrasive wear and adhesion.

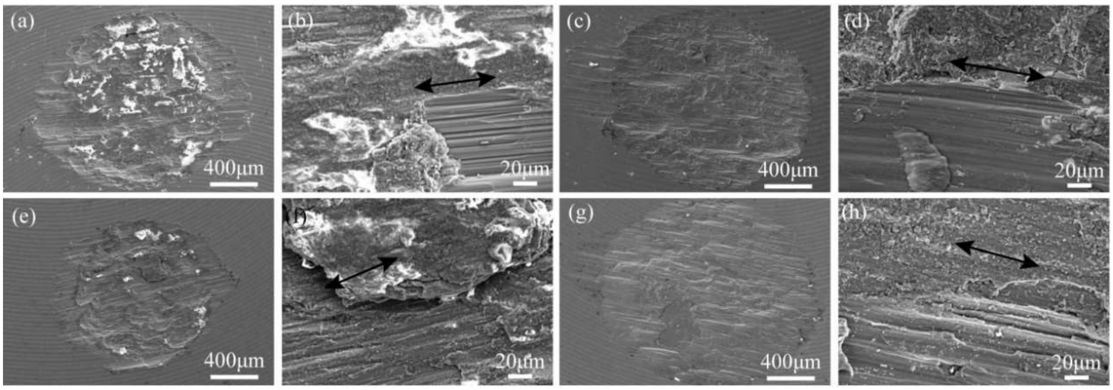

Figure 12. Wear morphology at different frequencies, dry friction in as-cast states: (a) and (b) 10 Hz, (c) and (d) 300 Hz. Extruded dry friction: (e) and (f) 10 Hz, (g) and (h) 300 Hz. Load 20 N

With the influence of lubricating medium, the size of wear mark is obviously lower than that of dry friction. Furrows and a small amount of matrix spalling were observed on the surface of the cast sample. After repeated rolling deformation, tiny lamellar spalling was observed on the surface, as shown in Figure 13. However, the scratches on the surface of the extruded samples are small, but a large number of adhesive wear particles appeared, thus causing abrasive wear. Under lubrication conditions, the main wear mechanisms of samples are abrasive wear and slight delamination, which is consistent with literature reports[16].

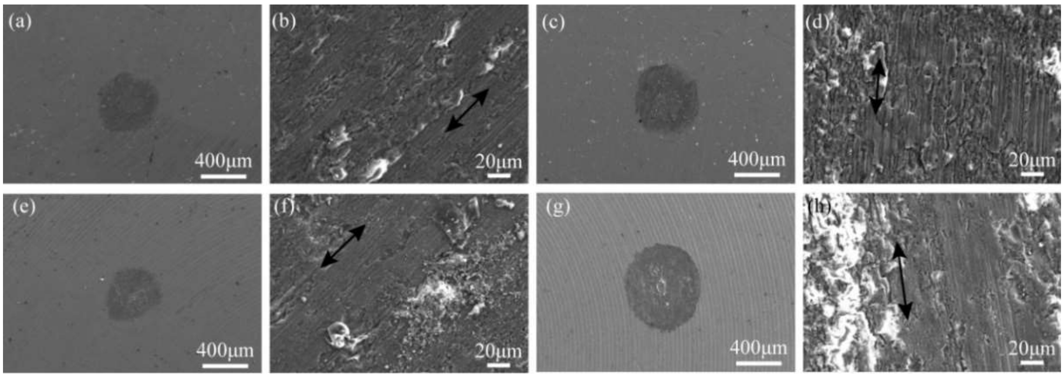

Figure 13. Wear morphology at different frequencies. Lubrication in as-cast states: (a) and (b) 10 Hz, (c) and (d) 300 Hz. Lubrication in extruded states: (e) and (f) 10 Hz, (g) and (h) 300 Hz. Load 20 N

Under dry friction condition, the friction coefficient of cast and extruded AZ31 magnesium alloy decreased gradually with the increase in fretting friction load (from 2 N to 100 N). With the increase in load, the wear amount first increased first and then decreased. Under lubrication condition, the change of friction coefficient and wear quantity is small. Under dry friction and lubrication conditions, with the increase in fretting friction frequency from 10 Hz to 300 Hz), the friction coefficient and wear amount of cast and extruded AZ31 magnesium alloy slightly increased. With the increase in load, the difference in friction coefficient and wear volume between as-cast and extruded state and the difference in fretting wear resistance are small. The effect of normal load on the fretting wear behavior of these alloys can be explained using Hertzian contact theory. Hertzian contact diameter for ball and flat configuration is expressed as follows:

$$D = 2\left[\frac{3FR}{4E^*}\right]^{1/3}$$

and:

$$\frac{1}{E^*} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2}$$

where,

F is the normal load, R is the ball radius, E_i is Young's modulus, and v_i is the Poisson's ratio the respective contacting materials.

The increase in Hertzian contact diameter interaction caused an increase in contact area. Therefore, wear mechanism was transformed from mild to severe, thus increasing the wear volume of magnesium alloys.

In the process of fretting wear, the material surface was subjected to large contact stress and frequent plastic deformation, resulting in the appearance of small cracks on the surface. Considering the brittleness of the material, magnesium alloy debris are more easily formed, resulting in abrasive wear. With the increase in load, the wear of magnesium alloy changed from slight to severe. Under the action of rapid reciprocating deformation strengthening, the abrasive debris are easily separated from the surface and form abrasive[17]. The presence of abrasive reduced the stable state of friction coefficient[11, 18, 19].

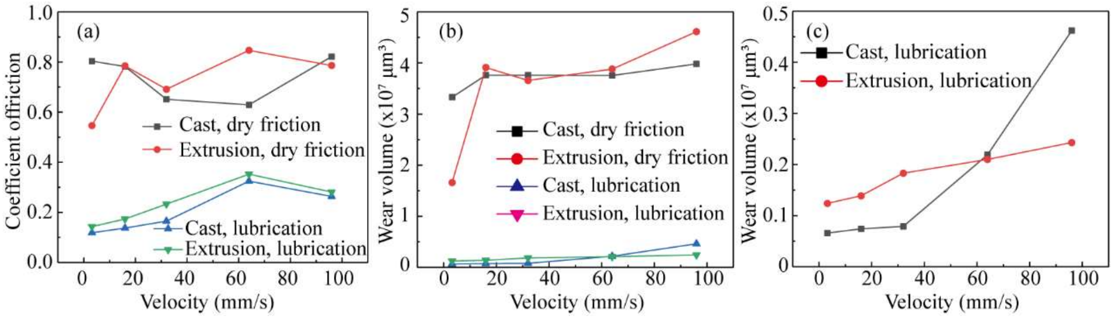

Figure 14. Variation of friction coefficient and wear volume at different speeds. (a) Friction coefficient, (b) Wear volume, (c) Partial enlargement of (b).

Different frequencies indicate different relative sliding speeds of friction pairs at the same number of cycles and amplitude (Table 2). The friction coefficient and wear volume at different frequencies are converted into those at different velocities, as shown in Figure 14. The influence of frequency on wear includes two aspects. First, with the increase in frequency, the sliding speed increased, thus increasing the contact interface temperature, and then accelerating wear. At the same time, with the increase in frequency, the movement speed of the debris increased, and the debris was more easily taken out of the contact interface, thus reducing wear. Second, with the increase in frequency, the oxidation time of material surface was short, the number of hard oxidation particles was reduced, and abrasive wear was reduced. The increase of mechanical properties did not remarkably increase the fretting wear resistance of magnesium alloy after extrusion. Especially under lubrication condition, the difference of friction coefficient and wear amount between cast and extruded AZ31 magnesium alloy is small.

Under dry friction condition, with the increase of load, the wear debris accumulated towards the center and edge of the wear marks. A delamination theory for wear that propagates through sub-surface cracks, resulting in the detachment of plate-like particles of the substrate[20, 21]. The fretting crackdepending on contact loading are mainly observed under gross slip regime[22], whereas fretting induced wear are encountered in partial and/or gross slip regime[23]. Under different loading conditions, the center of wear marks of cast and extruded magnesium alloy mainly involved adhesion, and the edge of wear marks mainly involved abrasive wear. Moreover, the number of abrasive particles on the wear surface of the extruded magnesium alloy is less than that of the corresponding casting sample. With the increase in the frequency of casting and extrusion samples, the amount of abrasive on the surface of the wear marks decreased gradually.

The average relative motion speed of friction pair is larger than that under low speed condition under high frequency reciprocating motion condition. At high speed, it is difficult to backfill the lubricating grease after it is extruded from the friction interface, resulting in the lack of oil lubrication at the friction interface[24]. Due to the lack of oil, the thickness of the oil film on the friction interface becomes thinner. The friction interface is actually in the state of dry friction or boundary lubrication[25]. The average linear velocity of friction motion is greater than 30 mm/s when the frequency is greater than 100Hz. Both the friction coefficient and the wear amount show a trend of increasing greatly (Fig. 14c).

The adhesion wear of AZ31 magnesium alloy is more obvious at high frequency (300 Hz). The number of abrasive particles in the extruded samples is less than that in the cast samples, and this phenomenon is mainly caused by adhesion wear. Casting mainly involves abrasive wear and adhesion. Under lubrication condition, the wear of cast and extruded samples is light, and the main wear mechanism is abrasive wear and slight peeling.

4. Conclusion

The friction coefficients of cast and extruded AZ31 magnesium alloys increased with the increase in load under dry friction condition. The friction coefficients first increased and then decreased with the increase in frequency. Under the same conditions, the friction coefficient of cast and extruded alloy has little difference.

Under dry friction conditions, the main damage mechanism of fretting wear of cast and extruded AZ31 magnesium alloy changed from abrasive wear to adhesive wear with the increase in load and frequency. The abrasive quantity of the wear surface of the extruded alloy was lower than that of the as-cast alloy, and the damage mechanism of the extruded alloy mainly involved adhesion wear.

The wear surface of cast and extruded AZ31 magnesium alloy has only slight abrasive wear and tiny exfoliation under lubrication condition. Both the friction coefficient and the wear amount show a trend of increasing greatly due to the oil lack of friction interface when the frequency is greater than 100 Hz.

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