Wear Behaviors and Wear Mechanisms of Wrought Magnesium

Alloy AZ31 Fabricated by Extrusion-Shear

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Abstract: Extrusion-Shear (ES) process for magnesium alloy is a newly developed plastic deformation technique which combines direct extrusion (DE) with ECAP(equal-channel angular pressing). Grains of ES-processed magnesium alloys can be refined effectively and mechanical properties can be improved, but the tribological properties have not been studied. In this study, the wear behaviors and wear mechanisms of AZ31 magnesium alloy samples produced by direct extrusion (DE) and extrusion-shear (ES) technologies, respectively, have been evaluated by friction coefficient and wear frequencies obtained from the dry sliding tests conducted at different loads and frequencies by using a high speed dry sliding test machine. SEM and EDS analyses technologies also have been used to analyze the wear surfaces and wear debris in different friction conditions. Based on the results, the ES-processed samples show a better wear resistance than those prepared by DE process as the ES-process samples show a lower friction coefficient comparing to those fabricated by DE process at the same conditions of loads and wear frequencies. With the increase of normal loads and reciprocating frequencies, the wear mechanism change from mild wear (adhesion, abrasion and oxidation) to severe wear (delamination, plastic deformation and melting). Therefore, the extrusion ways have significant influences on the wear behaviors of the samples and that the wear resistance of AZ31 magnesium alloy can be improved by extrusion-shear.

Key words: Extrusion-Shear, Microstructures, Wrought Magnesium, Wear Behaviors

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1. Introduction

Magnesium alloys have been widely used in the automotive industries as they can meet the requirements from the industries due to their outstanding strength, good ductility, high toughness and other mechanical properties. However, they can be applied to cylinders due to their poor wear resistance in dry sliding friction condition compared with the traditional wear-resistant materials, which is caused by their low strength at high temperature. A large amount of heat would be produced during the sliding process due to the high friction coefficient of magnesium alloys and this will limit their application in places subjected to sliding friction, such as the movement of automobile brake, the engine components including piston and cylinder bore, et al.

During the past decades, various of studies have been conducted to investigate and improve the friction and wear behavior of magnesium alloys and related system. Iglesias et al.^[1] has studied the tribological behavior of nanocrystalline oxygen-free high conductivity (OFHC) copper and commercially available pure titanium produced by large strain extrusion machining (LSEM), and he found that the refinement of the microstructures could reduce wear factors. Based on the results of ball-on-disc friction tests, Wang et al.^[2] observed that the overall friction coefficients increase significantly with the increase of the testing temperatures. Anasyida et al.^[3] has studied

effects of cerium addition on wear behaviors of as-cast Al-4Si-4Mg alloys. Anbuselvan et al. ^[4] investigated the wear behavior of as-cast ZE41A magnesium alloy during dry sliding. Ying et al. ^[5] used dry friction reciprocating sliding motion to research the friction and wear behavior of AZ91D magnesium alloy fabricated with conventional casting and thixoforming casting, which is counterposed against GCr15 steel. By wear test, Y. Fouad et al. ^[6] investigated the wear behaviors of wrought magnesium alloy AZ31 samples with/without different surface treatments. By ball-on-disc tests under three different loads at a constant sliding velocity, P. Bala Srinivasan et al. ^[7] compared the dry sliding wear behaviors of a conventional and a recycled magnesium alloys produced by high pressure die casting. The recycled alloy showed a lower friction coefficient and a lower wear rate compared to the conventional alloy due to the higher hardness and relatively higher volume fraction of β -phase with a denser distribution near the surface.

There are also some studies have investigated the wear behavior of hot extruded alloy produced by equal-channel angular pressing (ECAP) which developed in the early 1980s. Using dry sliding tests, Srinivasan et al. ^[6] evaluated the wear behaviors of AZ31B alloy and nano-composite, which were manufactured by hybrid casting process and hot extruded at 350°C, at room temperature using the standard pin-on-disc wear test equipment. Wear behaviors of hot extruded Al-Si and Al-Mg alloys under dry conditions, and ZE41A magnesium alloy have been studied by Demirci et al. ^[8] and Anbuselvan et al. ^[9]. Magnesium alloys with high strength and toughness have been obtained by Segal et al. ^[10] and Matsuyama et al. ^[11] and using equal channel angular extrusion (ECAE) which usually includes more than 2 steps. Besides, the materials in ECAE have to endure intricate diversification of forming environments, such as process temperature, and may be oxidized. In addition, ECAE only available in the lab scale processing for nano crystalline

material, and there exist an unbridgeable gap between the experimentation and applications of industry ^[12]. By combining direct extrusion (DE) and two steps of equal channel angular pressing in a single process, Orlov et al. ^[13] obtained a material with an excellent balance of strength and tensile ductility. Therefore, it is necessary to improve the wear resistance of magnesium alloy by the advanced developed forming methods.

A new severe plastic deformation method named extrusion-shear technology (shorten for “ES”) was developed to fabricate the fine grained magnesium alloys. The composite extrusion method for magnesium alloy combines traditional extrusion and ECAP (equal channel angular pressing), that is to say extrusion and shears are combined, by performing initial forward extrusion and shearing process subsequently. As an earlier research group studying in ES process, various studies have been conducted. Based on our former studies^[14-16] ES process is well suit for manufacturing long, straight products with a constant cross-section using direct extrusion and two steps ECAP which exerts local back pressure and shear force on materials at the turn corners. It could improve the workability and strength of magnesium alloys by refining the grains, and has bright prospect of application in the industries.

However, the level of accuracy need to be improved even through various kinds of rods with desired final dimensions could be produced. This sustainable high level of accuracy could be achieved by precisely adjusted and utilized. In addition, process parameters must be carefully checked in order to ensure a high level of quality in production. In this study, the wear morphologies of magnesium alloy fabricated by ES have been compared with which of AZ31 magnesium alloy prepared by DE. The effects of ES process on the friction and wear properties of magnesium alloy have been discussed.

2. Experimental procedures

The samples used in this study were AZ31 magnesium alloys fabricated by ES process with two consecutive processes combining initial direct extrusion and subsequent successive shearing, in which forming with two shearing and extruder with different structures installed has been applied. After that, the dry sliding friction tests were carried out using the high speed dry sliding test machine with reciprocation frequencies of 2, 4, 6, 8 and 10 HZ, exerted load of 5 N, testing duration of 10 min and stroke length of 10 mm. The dry sliding wear tests of extruded specimens have been conducted with a HSR-2M high speed reciprocating friction tester at room temperature. Variations of friction coefficients and wear rates with different loads and frequencies have been studied, in which a GCr15 steel sphere with a diameter of 3.0mm has been used as the friction pair of AZ31B. The volumetric wear losses at different positions were examined on the worn surface using NanoMap500LS surface scanning contour graph, and the morphologies of worn surfaces were observed by JSM-6460LV style scanning electron microscope.

For microstructures analysis, the magnesium specimens with size of 20 mm x 15 mm x 5mm were cut from the alloy by line cutting, prepared with the standard metallographic procedures, and etched with picric acid based etchant composing of 5.5g picric acid, 100ml alcohol, 5ml acetic acid and 10ml distilled water. Then, the microstructures were revealed by metallographic scope and image analyzer (OLYMPUS made in Japan). Besides, the phase compositions and micro-hardness of the specimens have been studied by AD5000X X-ray diffract meter and HVS-1000 digital micro indentation tester with a normal load of 100g, respectively. The final experimental results used for further analysis were averaged from 3 repeated tests aiming at minimizing the impact of the experimental errors.

3. Results and discussion

3.1 Effects of loads for dry sliding on the friction behaviors of wrought magnesium alloy

The friction coefficients of AZ31 magnesium alloy changing with the applied loads are shown in Figure 1 with the parameters used for the samples are illustrated. It can be seen that the friction coefficient of magnesium alloys decreases with the increase of exerted loads in dry sliding tests. This is because the contact points and the contact areas of friction pairs will increase with the rising of the loads. Besides, as the relationship between the actual contact areas of surface and the load is nonlinear, the friction coefficient shows some nonlinear decline. In addition, the samples fabricated by ES processes have a lower friction coefficient under various loads in dry sliding tests comparing to that produced by DE.

From the volume wear frequency for dry sliding tests of magnesium alloy samples in Fig.2, it can be seen that wear frequency show a similar changing trend with friction coefficient that the wear frequency will increase with the rise of the exerted loads and the ES-processed samples show a lower values that that from DE.

The repeated action of the applied loads causes the materials to produce plastic deformation, which is driven by the dislocation slip and the formation of micro cracks. Crack propagation of the surface occurs, and the material falls off, so wear occurs. The loads are larger, and the wear is more serious. On the other hand friction forces could generate a large amount of friction heat with the load increase. Wear resistance of the alloy is reduced by softening material of sample surfaces. At the same time, the micro cracks improve wear and tear further.

Fig. 1 Curves of friction coefficient varying with the different loads of dry sliding

Fig. 2 Curves of wear frequency varying with the different loads of dry sliding

3.2 Effects of the frequency for dry sliding on the wear properties of magnesium alloy

The effects of frequency on the friction coefficient and the volume wear frequency are shown

in Fig. 3 and Fig.4. The other parameters set in the tests are listed in the Figures. Fig.3 shows that the friction coefficient of the wrought magnesium alloy will first decrease with the rise of the frequency, but it will begin to increase at a certain frequency, around 6HZ. The subsequent growth is slow and friction coefficient slightly tend to be a constant. Besides, at low frequency, the friction coefficient of the direct extruded magnesium alloy is significantly higher than that fabricated by ES deformed process. Overall, the average friction coefficient of the samples for Magnesium alloy fabricated by ES process is between 0.08 and 0.16, and which of the direct extruded samples are between 0.05 and 0.12.

Fig. 3 Curves of friction coefficient varying with the reciprocating frequency of dry sliding

Fig. 4 Curves of wear frequency rates varying with the reciprocating frequency of dry sliding

The volumetric wear frequency rates changing trend with the varying of frequency are shown in Fig.4. Generally, the wear frequency rates decrease with the increase of the frequency and the wear rates from the ES-processed samples are lower than those from the samples processed with DE process. The reciprocating frequency will affect the wear properties of magnesium alloy through the risen temperature between the contact surfaces results from the friction heat in the dry sliding tests. It is known that the friction heat and the temperature at the contact areas will increase with the increase of the reciprocating frequency due to the repeated frictions. At the beginning, the surface of magnesium alloys exposed in the air are more easier to be oxidized to form oxide films due to the lubricating effect, which could reduce the contact forces between the friction pairs, weaken the adhesion of the interface, and reduce friction forces. So it can be seen that the friction coefficient and wear frequency decrease with the rise of frequency at first. However, with the rapidly accumulation of the friction heat generated in the repeated frictions due to the increase of the reciprocating frequency, the temperature will continue to rise and this will cause the material soften at a certain critical value. Then, this will further lead to the plows of the contact surfaces,

which results in the increase of the friction coefficient, as shown in Fig. 3.

3.3 Friction and wear surface morphologies of ES extruded magnesium alloy

The worn surfaces of the morphology of ES extruded AZ31 magnesium alloy tested by dry sliding under various load conditions at 6HZ are revealed by the scanning electron microscope (SEM), as can be seen in Fig. 5. Under the load of 5N, morphologies of the worn surface are grooved with different shapes and sizes with adhesive wear debris pulled up in some positions due to a portion of materials on the sample surface changed into balls during dry sliding process, which is a typical of adhesive wear characteristics. Some adhesive transferred fragments may break off and become free abrasive grains as the sliding continues. These small particles are sandwiched between the friction pairs and a few of them works as abrasive grains, which could scrape the surfaces of the magnesium alloys and further form the friction surface. Besides, the shear sliding on magnesium alloy with soft plastic flow will form ridges, which also have effect of the furrow formation. Therefore, the wear mechanisms of friction process contains adhesive wear and abrasive wear.

As the load increased to 15N, the worn surface of the contact areas became worse and increased significantly, as shown in Fig.5b. Under the SEM, it can be seen that there are widened grooves, localized plastic deformation and larger broken area on the worn surface. In addition, there are also some signs of peeling and material transfer occurred.

Fig.5 The worn surface morphology of ES extruded AZ31 magnesium alloy under different loads (6HZ)

Fig. 6 The worn surface morphology of ES extruded AZ31 magnesium alloy at load of 15N and reciprocating frequency of 6HZ.

The EDS energy spectrum analysis presents oxygen element diffraction peaks, as shown in Fig.6. This indicates that the contact surfaces were slightly oxidized during the dry sliding process, which indicates oxidation wear occurred. The friction surface became rougher with the going of

dry sliding test. The alternating contact stress also affects the contact surface, which may promote the surface crack initiation containing friction crack and shear crack which could extend to the surfaces and further make the materials fall off results in surface presenting pits or crush. This is how the fatigue wear occurred. Therefore, the main wear mechanisms in the reciprocating friction of dry sliding are the oxidation wear, abrasive wear and fatigue wear.

3.4 Wear morphologies of direct extruded magnesium alloy

The worn surfaces of the direct extruded magnesium alloy from dry sliding tests under various conditions were observed by the SEM, as shown in Fig.7. At the load of 5N, the worn surface from the DE-processed sample is full of furrows which are much more deeper and wider compared to those from ES-processed samples as illustrated in Fig. 6. There are also a small amount of black oxide particles attached to a pole and occluded of the furrows indicating a slight peeling phenomenon occurred, which is caused by severe adhesive wear. In addition, slight delamination wear and oxidation wear also have occurred. Thus, the wear mechanisms of the condition are mainly adhesive wear and abrasive wear, and the wear degree of magnesium alloys fabricated by DE is deeper than those fabricated by extrusion-shear.

Fig. 7 Surface morphology and EDS analysis of direct extrusion of magnesium alloy with different loads at frequency of 6 HZ: (a-c) SEM photograph, (d) EDS Atlas (load is 15N)

As the loads of dry sliding increased to 15N, a large number of small black particles attached to the worn surface were observed, which means oxidation abrasion happened, as illustrated in Fig.7b. With EDS, a stronger diffraction peaks of oxygen element presents in the black particles, as can be seen in Fig.7d, which verifies that the black particles are oxide particles. Besides, the intensity of the oxygen element is obviously higher than those in the Fig.6, which means that the oxidation and wear of the DE-produced magnesium alloy is serious than that in the ES-produced alloy under the same dry sliding conditions. This is because with the rising of loads, the temperature of the contact surfaces increase and they are more likely to be oxidized. As shown in Fig.7c, the friction surface of the magnesium alloy is partially melted under the load of 25N, which is because the temperature of surfaces reached the melting point of AZ31 magnesium alloy due to a large amount of friction heat comes from the dry sliding tests under high contact pressures. The contact pressure could also drive the melt of the material out of the contact surfaces. As the dry sliding going on, the extruded material continuously forms a new multilayer structure on the original surface layers lending to the occur of thermal wear, as illustrated in Fig.7c. The

worn surface looks smoother than other worn surfaces due to the lighter degree of the stripping layer. Thus, the main wear mechanism of magnesium alloy is thermal wear including delamination wear and other wear. Therefore, in dry sliding test, the AZ31 magnesium alloy produced with DE was characterized as oxidation wear and abrasive wear under low loads and delamination wear and adhesion transfer onto the counterpart under very high normal load.

Under the same dry sliding condition, the wear patterns of samples from DE process and ES process are similar while their dominant wear mechanisms are quite different. Comparing to the samples prepared by ES process, the samples from DE process have a more higher wear degree with a rapid transition from slight wear to severe wear. This is because the volume wear frequency of magnesium alloy prepared by DE process is bigger than those fabricated by ES process. Therefore, it is clear that wear resistance of AZ31 magnesium alloy can be improved by extrusion-shear.

3.5 Wear debris morphologies and energy spectrum analysis

The wear debris generated during dry sliding tests were collected and analyzed using SEM and EDS energy spectrum as they are also an important basis used for judging the wear mechanism of friction surfaces. The mild wear usually produce small debris with typical size of 0.01-1 μ m while severe wear generate larger debris with a typical size between 20-200 μ m. The fine particles with black powder and metallic luster can be found in them. The detail results are shown in Fig. 8.

As shown in Fig.8a, there are some small size particles, irregular particles, larger thin sheet and elongated grains in the debris from the ES produced samples. There are also some abrasions streaks on the surface of flake debris, which could be formed by repeated loading and unloading.

Besides, the surface of the chip is relatively smooth as it was directly peeled off surface of specimens. A small amount of wear debris are strip or curved shape with the characteristics of cutting debris coming from the edge of grinding surface and furrow plough ridge. The irregular abrasive particles were formed by brittle fracture and adhesive wear, and the diffraction peaks of oxygen element presented in the EDS energy spectrum analysis, as shown in Fig. 8b, which indicates that there are some MgO particles in the debris leading to the conclusion that oxidation wear did occurred.

The wear debris morphologies of magnesium alloy fabricated by DE is shown in Fig.8c. It can be seen that it mainly includes a large number of thin sheet-shaped abrasive particles and strip-shaped abrasive particles. Compared with the wear debris of the samples form ES process, there is no plough on the surface of flake abrasive grains with relative small sizes and irregular shapes on the samples produced with DE. The formations of this wear debris are probably due to the brittle fracture spalling from the surface of the specimen. The occurrence of oxidative wear mechanism is verified as the oxygen element diffraction peak present in the EDS analysis, as can be seen in Fig.8d. Therefore, the main wear mechanisms are abrasive wear, delamination wear and oxidation wear.

Fig. 8 SEM of the chip and EDS analysis of the magnesium alloy debris comes from dry sliding tests at load of 5N and frequency of 6HZ : (a, b) extrusion-shear and (c, d) direct extrusion

4. Conclusions

In this study, the wear behaviors and wear mechanisms of AZ31 magnesium alloy samples fabricated by direct extrusion (ES) and extrusion-shear (ES) technologies, respectively, have been investigated using dry sliding tests at different loads and frequencies with high speed dry sliding test machine. The friction coefficient and wear frequency have been used to evaluate the wear properties of deformed magnesium alloys. SEM and EDS analyses technologies also have been applied to analyze the wear mechanisms in different friction conditions.

Based on the results, ES-process magnesium alloy samples have a lower friction coefficient than those prepared by DE at the same conditions of loads and wear frequency. It turns out that the ES-processed samples show a better wear resistance than those prepared by DE process. The wear mechanism change from mild wear (adhesion, abrasion and oxidation) to severe wear (delamination, plastic deformation and melting) with the increase of normal loads and

reciprocating frequencies. All in all, the extrusion ways have great influences on the wear behaviors of the samples and that the wear resistance of AZ31 magnesium alloy can be improved by extrusion-shear.

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