Investigation on Dynamic Friction Properties of Extruded AZ31 Magnesium Alloy Using by Ring Upsetting Method*¹

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The dynamic friction properties of the extruded AZ31 magnesium alloy of the grain size of 20 μm were investigated by ring upsetting method test at 523, 548 and 573 K at strain rate of $1.0 \times 10^{-2} \text{ s}^{-1}$, where all the initial testing conditions were the climb-controlled dislocation creep. The MoS_2 lubricant maintained lower dynamically friction coefficient (m value) than the oil lubricant. The difference in m values between machined surface and polished surface was unclear. The m values for WC-Co and diamond like carbon (DLC) tools were similar in MoS_2 lubricant. The m values for DLC tool were lower than those for the WC-Co tool in the oil lubricant. The extruded direction influenced to the friction properties. The aspect ratio of the inner diameter on 90° to extruded direction after testing was almost isotropic; on the other hand, the anisotropy occurred on 0° and 45° . The extent of anisotropy at 548 K was the highest, although the lower temperature, the higher the critical shear stress of non-basal plane. The condition at 523 K, where the fine grain sizes less than 3 μm could be obtained by dynamic recrystallization during deformation, is suitable temperature to make superplasticity at the given strain rate. [doi:10.2320/matertrans.P-M2010811]

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1. Introduction

Lighter and more compact devices are desired in order to aspire for high recycling-based society and ubiquitous society. Magnesium and its magnesium alloys have attracted a great deal of attention because of its lightness and high potential in recyclables. Many components of the mobile electric appliances, such as chassis of cellular phones, notebook computers and mini-disk players, automobile chassis and so on, have been produced by using magnesium alloys.

Now one of the major processing for magnesium products is die-casting, that has some drawbacks such as less reliability and lower industrial productivity: an easy initiation of the some cast defects, difficulty in molding with thin wall, burr cause easily due to low viscosity of the molded magnesium and so on.¹⁾ In order to spread magnesium alloys to more engineering applications, therefore, new development in plastic forming process is expected. Recently there have been many reports about information on the research and development for the possible plastic forming of the magnesium alloys.^{2–16)}

The characteristics of magnesium and its magnesium alloys have low ductility around room temperature, because the critical shear stresses on non-basal slips are relatively much higher than that on basal slip, due to their hexagonal close packed (HCP) structure. However, ductility of the magnesium alloys is improved at elevated temperature because the critical shear stresses on non-basal slips decrease

remarkably and the difference of the critical shear stresses between basal slip and non-basal slips becomes smaller or negligible. In addition, it has been reported that both of the significant higher ductility and the lower stress are achieved with decreasing grain size in the magnesium alloys resulting from superplasticity.^{12–16)} Plastic forming at elevated temperature is highly expectable as a process to the magnesium products.

Interactive friction property between the deformed materials and the tools is one of the important factors for plastic forming process, because formability is strongly affected by it. Koga and Paisarn⁶⁾ indicated that the formability for AZ31 magnesium alloy is almost same to those for steel and aluminum alloy as a result of low friction coefficient. On the other hand, in the case of rib forming, the low friction causes some surface defects by material overflow from an opposite sheet side, which might indicate a possibility of the requirement of the higher friction coefficient.

As described above, it is important to investigate the friction properties of the magnesium alloy at elevated temperature for optimizing the sound forming process comprehensively. The purpose of this study is to investigate the dynamic friction properties at the elevated temperatures for the extruded AZ31 magnesium alloy in the viewpoint of the lubricant, the surface roughness of the specimens, surface materials of the tools and the microstructures of the specimens.

2. Experimental Procedures

2.1 Materials

The material used in this work is an extruded AZ31 magnesium alloy. The chemical composition is shown in

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Table 1 The chemical composition of AZ31 (mass%).

Al	Zn	Mn	Fe	Si	Cu	Ni	Ca	Mg
2.80	0.82	0.87	0.0022	0.022	0.001	0.0008	0.001	Bal.

Fig. 1 Optical micrograph of extruded AZ31 magnesium alloy.

Fig. 2 (a) (0002)L and (b) (10 $\bar{1}$ 1)T pole figures of extruded AZ31 magnesium alloy.

Table 1. The optical microphotograph of the extruded AZ31 magnesium alloy before the ring upsetting testing is shown in Fig. 1. The extruded direction is horizontal. The material has almost equiaxed grains but elongated grains paralleled to extruded direction. The grain sizes ranged 10 to 100 μm and the mean grain size is 20 μm . The pole figures of the extruded AZ31 magnesium alloy bar were measured for (0002)L from the parallel plane to the extruded direction and (10 $\bar{1}$ 1)T from the vertical plane to the extruded direction and these results are detected in Fig. 2. The c -axis is perpendicular to the extruded direction and is directed to the circumference from center.

2.2 Test for dynamic friction property

The dynamic friction coefficient (m value) was determined by employing the ring upsetting method.¹⁷⁾ The Instron-typed compression testing machine with furnace was used for it. The conditions of the ring upsetting testing are shown in Table 2. The specimens were deformed to the fixed strains at 0.4 and 0.5 at the temperatures of 523, 548 and 573 K and a

Table 2 The conditions in the compression test.

Temperature, K	523, 548, 573
Strain Rate, s^{-1}	1×10^{-2}
Strain	0.4, 0.5
Materials	0°, 45°, 90° to extruded direction
Surfaces of Material	Machining, Polishing
Surfaces of Tools	WC-Co, Diamond Like Carbon (DLC)
Lubricants	Oil, MoS ₂

Fig. 3 The calibration curve for dynamic friction coefficient.

strain rate of $1.0 \times 10^{-2} \text{ s}^{-1}$. The m value was described by calibration curve between compression rate, R_e , and reduction rate of inner diameter, E , which are given by:

$$R_e = \frac{H - h}{H} \quad (1)$$

$$E = \frac{D_i - d_i}{D_i} \quad (2)$$

where H is the initial height of the specimen, h is the height of the specimen after the ring upsetting test, D_i is the initial inner diameter of the specimen and d_i is the inner diameter of the specimen after the ring upsetting test. The calibration curves for m values are shown in Fig. 3. The ring specimens with 4 mm in height, 6 mm in inner diameter and 12 mm in outside diameter were machined from the extruded bars by the electro-discharge method, where the angles between the compressive direction and the extruded direction were 0, 45 and 90 degree (hereinafter called the 0° to extruded direction, the 45° to extruded direction and the 90° to extruded direction, respectively), as described in Fig. 3. The two kinds of the surface roughness were prepared for the specimens; machining surface and polishing surface, and besides, the two kinds of the materials were prepared on the surfaces of

Table 3 The values of the constitutive equations and the values for diffusion coefficients in magnesium alloys.

Deformation Mechanism	A	n	p	D	Ref.
Slip-accommodated grain boundary sliding	1.8×10^6	2	2	$D_L + 1.7 \times 10^{-2}(\pi/d)\delta D_{gb}$	19–21)
Glide-controlled dislocation creep	3.0×10^{-2}	3	0	D_s	22)
Climb-controlled dislocation creep	8.0×10^4	5	0	$D_L + 2.0 \times 10^9(\sigma/G)\delta D_{gb}$	23)
Diffusion Coefficient	$D_0/\text{m}^2/\text{s}$			$Q/\text{kJ/mol}$	Ref.
D_L	1.0×10^{-4}			135	24)
D_s	1.2×10^{-3}			143	24)
D_{gb}	5.0×10^{-12} ($\delta D_0/\text{m}^3/\text{s}$)			92	24)

the tools; WC-Co cemented carbide and the diamond like carbon (DLC) with the mean surface roughness, R_a , of 0.09 μm and 0.15 μm , respectively. The commercial oil and molybdenum disulfide (MoS_2) were used as lubricants in this work.

3. Deformation Behaviors

The constitutive equation for elevated temperature deformation is generally expressed as:¹⁸⁾

$$\dot{\epsilon} = A \left(\frac{Gb}{kT} \right) \left(\frac{b}{d} \right)^p \left(\frac{\sigma - \sigma_{th}}{G} \right)^n D \quad (3)$$

where $\dot{\epsilon}$ is the strain rate, A is a constant, G is the shear modulus $\{= E/(2 \times (1 + \nu))\}$, E is the Young's modulus $[= 4.3 \times 10^4 \times (1 - 5.3 \times 10^{-4} \times (T - 300))]$, ν is Poisson's ratio and T is the absolute temperature, b is the Burgers vector, k is the Boltzmann's constant, d is the grain size, p is the grain size exponent, σ is the flow stress, σ_{th} is the threshold stress, n is the stress exponent and D is the diffusion coefficient $\{= D_0 \exp(-Q/RT)$: D_0 is the pre-exponential factor for diffusion, R is the gas constant, Q is the activation energy}, which are dependent on the rate controlling process. It is reported that the magnesium alloys have three modes of the deformation for the possible mechanisms in the strain rate range for plastic forming: (i) slip accommodated grain boundary sliding process, which is accepted as the dominant deformation mechanism for superplastic flow, (ii) glide controlled dislocation creep and (iii) climb controlled dislocation creep. The sets of the parameters in eq. (3) to express the corresponding deformation processes in AZ31 magnesium alloy are listed in Table 3, where the diffusion coefficient and shear modulus of AZ31 magnesium alloy were taken to be those of the pure magnesium. The relationship between flow stress and strain rate at the temperatures of 523, 548 and 573 K is shown in Fig. 4. Due to independence for each mechanism, the fastest mechanism appears deformation behavior for materials. The predicted deformation behaviors with grain size of 20 μm , which is the mean grain size of the extruded AZ31 magnesium alloy used in this work, are indicated by bold lines. It is noted that the AZ31 magnesium alloy used in this work indicates the climb controlled dislocation creep with the strain rate of $1 \times 10^{-2} \text{ s}^{-1}$ at all the testing temperatures.

Fig. 4 Variations in stress as a function of strain rate at (a) 523 K, (b) 548 K and (c) 573 K for magnesium alloy.

4. Results and Discussion

The m values with the testing temperature are shown in Fig. 5. Comparing the effect of the lubricants on m values, those for MoS_2 lubricant were basically lower than those for oil lubricant, and maintained the low value below 0.3 at all the testing temperatures. On the oil lubricant, however the m value at 573 K is higher than that at 548 K, indicating that the lubricative property of the oil lubricant deteriorates at 573 K.

Comparing the effect of the surface roughness of the specimens on the m values, the difference between the machined and the polished surfaces was a little. It is suggested for the extruded AZ31 magnesium alloy that some specific treatments on the surface condition are not necessary

Fig. 5 Friction coefficient with testing temperature (a) 0 degree to extruded direction with Oil, (b) 0 degree to extruded direction with MoS_2 , (c) 45 degree to extruded direction with Oil, (d) 45 degree to extruded direction with MoS_2 , (e) 90 degree to extruded direction with Oil and (f) 90 degree to extruded direction with MoS_2 .

for plastic forming process at the elevated temperatures. Comparing the effect of the materials for the surface of the tools on m values, there was almost same between WC-Co and DLC in the case of using the MoS_2 lubricant. However, the m values for WC-Co tool are higher than those for DLC in the case of using the oil lubricant. As aforementioned, it is noted that a selection of the lubricant and the surface materials of the tools is one of the major key factors to control m value during forming for the extruded AZ31 magnesium alloy. It can be also noted from Fig. 5 that the different behaviors in m values occur for the each extruded direction of the specimens. It is considered that the crystal orientation influences to the dynamic friction properties for the extruded AZ31 magnesium alloy.

Confirming that, the variations in aspect ratio of the inner diameter as a function of the temperature for the each

extruded direction were measured and the results are detected in Fig. 6. In the 0° to the extruded direction, it was inclined that the values of the aspect ratio at 548 K were the highest. The lowest values were obtained at 523 K for each testing condition. In the 90° to extruded direction, the values of the aspect ratio were around 1 at any temperature, which may be due to isotropy. In the 45° to extruded direction, the trend of the aspect behavior was same to that in the 0° to extruded direction, and the values of the aspect ratio in the 45° to extruded direction were higher than those in the 90° to extruded direction and lower than that in the 0° to extruded direction.

Critical shear stresses on non-basal slip remarkably decrease with increasing temperature and the difference between those on non-basal slip and basal slip is a little, but those on non-basal slip are still higher than that on basal slip

Fig. 6 Variations in aspect ratio of inner diameter as a function of temperature for (a) 0° to extruded direction, (b) 45° to extruded direction and (c) 90° to extruded direction.

at 573 K.²⁵⁾ Therefore, it is considered that the higher crystal orientation anisotropy the specimen had, the higher the values of the aspect ratio were, and moreover, those at 543 K were higher than those at 573 K.

However, there was partially discrepancy between the forgoing discussion and the experimental results—namely, the values of the aspect ratio at 523 K for the 0° and the 45° to extruded directions were lower than those at the other temperatures, although the difference between the critical shear stresses on non-basal slip and basal slip at 523 K is relatively higher than those at other temperatures. It is considered that the change of the microstructure influences to the deformation mechanism during compressive testing.

Takara *et al.* have studied the grain refinement and growing processes for AZ31 magnesium alloy and set up an equation for the critical grain size, d_{crit} , above which the grain refinement would occur during deformation.¹⁰⁾ The equation is given by:

$$d_{crit} = 650Z^{-0.2} \quad (4)$$

where Z is Zener-Hollomon parameter, ($= \dot{\epsilon} \exp(Q/RT)$). The critical grain size at the various temperatures for the AZ31 magnesium alloy tested at $1.0 \times 10^{-2} \text{ s}^{-1}$ calculated by the eq. (4) is shown in Table 4. All the grain sizes

Table 4 The critical grain size at the various temperatures for the AZ31 alloy with strain rate of $1.0 \times 10^{-2} \text{ s}^{-1}$.

Temperature/K	523	548	573
Critical grain size/ μm	3.2	4.3	5.6

Table 5 Dynamically recrystallized grain size at the various temperatures for the AZ31 alloy with strain rate of $1.0 \times 10^{-2} \text{ s}^{-1}$.

Temperature/K	523	548	573
Dynamically recrystallized grain size/ μm	2.9	4.7	7.2

Fig. 7 A typical microstructure observed in the specimen after the ring upsetting test at 523 K.

calculated by the eq. (4) were smaller than the initial grain size of $20 \mu\text{m}$ observed in the current materials, meaning that the grain refinement process would occur during deformation at all the testing temperatures for the extruded AZ31 magnesium alloy. A typical microstructure after the ring upsetting testing at 523 K for the 0° to extruded direction is shown in Fig. 7. There were smaller grains about $3 \mu\text{m}$ in most area, sustaining the refinement process during deformation at the elevated temperature.

Watanabe *et al.* derived a phenomenological equation for the dynamically crystallized grain size, d_{rec} , for magnesium alloys, which is given by²⁶⁾

$$(d_{rec}/d_0)^1 = 10^3 \times Z^{-1/3} \quad (5)$$

where d_0 is initial grain size of specimen. The calculated dynamically recrystallized grain size at the various temperatures for the magnesium alloy with initial grain size of $20 \mu\text{m}$ is shown in Table 5. The calculated dynamically recrystallized grain size decreases with decreasing temperature. The calculated dynamically crystallized grain size at 523 K ($3.2 \mu\text{m}$) was good agreement with the grain size about $3 \mu\text{m}$ seen in Fig. 7. It was figured out from Fig. 4 that it is related to the superplastic behavior, considering that the deformation mechanism at 523 K was changed the dislocation climb into the grain boundary sliding as a result from the

dynamically recrystallization during the ring upsetting testing. This might be reason why the values of the aspect ratio at 523 K were lower than those at 548 K for 0° and 45° to extruded direction in spite of the stronger anisotropy at 523 K compared with those at 548 K and 573 K.

It is worth to investigate the effect of the dynamically recrystallization behavior on the dynamic friction properties as a future work.

5. Conclusions

The dynamic friction properties of the extruded AZ31 magnesium alloy were investigated by the ring upsetting method at the temperatures of 523, 548 and 573 K with the strain rate of $1.0 \times 10^{-2} \text{ s}^{-1}$ in the viewpoint of the lubricants, the surface roughness of the specimens, the surface materials of the tools and the microstructures of the specimens. The results were as follows.

- (1) The m values in the case using MoS_2 lubricant are about/below 0.3 in all the testing conditions, which were relatively lower than those in oil lubricant. In addition, those at 573 K were higher than those at 548 K in oil lubricant.
- (2) In the case of the surface roughness on the specimens; the machining surface and the polishing surface, the difference of the m value between them were unclear yet.
- (3) In the case of the materials on the surfaces of the tools, the m values were almost same in MoS_2 lubricant. On the other hand, these for WC-Co tool were higher than those for DLC in oil lubricant.
- (4) In the 90° to extruded direction, the values of the aspect ratio were around 1 at any temperature. In the 0° to extruded direction and the 45° to extruded direction, the values of the aspect ratio at 548 K was the highest and those at 523 K were the lowest. The dynamically recrystallization occurred during early deformation and its fine grain size obtained at 523 K resulted in a possible superplastic behavior.

It is suggested that the dynamic friction property is affected by the outer factors-namely, lubricant and surface materials of the tools and the inner factors, that is, crystal orientation of the microstructure, microstructural evolution during deformation and the followed change in deformation mechanisms. It is required to systematize the dynamical friction properties at various conditions in order to develop the new plastic forming processes for magnesium and its magnesium alloys.

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