Superplastic Behavior and Microstructural Evolution in a Commercial Mg–3Al–1Zn Magnesium Alloy

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Superplastic behavior and microstructural evolution in a commercial Mg–3Al–1Zn magnesium alloy were investigated at temperatures between 623 K and 723 K and strain rates between 10^{-5} and 10^{-3} s^{-1} . Grain refinement was obtained in the test alloy due to the dynamic recrystallization during an initial stage of tensile test. As a result, the alloy exhibited good superplasticity at all strain rates and temperatures, and a maximum elongation of 314% was obtained. The results of optical microscopy and SEM revealed that the dominant deformation mechanism was grain boundary sliding, and the dynamic recrystallization was the accommodated mechanism for the deformation.

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1. Introduction

Magnesium alloys are being increasingly used in automobile, electronics and aerospace industries due to their low density, high specific strength and specific stiffness, superior damping capacity, excellent machinability, good electromagnetic shielding characteristics and good castability.^{1–4)} However, magnesium alloys normally exhibit low ductility because of their hcp structure. As a result, most of structural magnesium products are fabricated by casting methods rather than by plastic forming technology such as forging, rolling and extrusion.^{5,6)} It is therefore necessary to improve their ductility in order to extend the use of magnesium alloys. Superplastic forming is a viable technique to fabricate hard-to-form materials into complex shapes.

It is generally considered that fine grain sizes of $\leq 10 \mu\text{m}$ are required to attain superplasticity in metals.⁷⁾ Many efforts have been made to refine the grain sizes of magnesium alloys in order to obtain high-strain-rate and low temperature superplasticity through powder metallurgy methods using rapidly solidified powders, extrusion with high reduction ratio and equal-channel-angular extrusion.^{8–10)} However, to date, only a few investigations have been made on the superplasticity of commercial magnesium alloys.^{11,12)} In comparison to castings, commercial wrought alloys have relatively small grain sizes in the as-received condition. Superplastic forming using commercial wrought alloys is economically attractive because complex thermomechanical processing is unnecessary. Therefore, the investigation of the superplastic behavior in commercial magnesium alloys is necessary.

The purpose of this paper is to demonstrate the occurrence of superplasticity in a Mg–3Al–1Zn magnesium alloy using commercial extruded bar, and to report some results on the superplastic behavior and microstructural evolution in the alloy.

2. Experimental

The material used in the present study was a commercial magnesium alloy in the form of an extruded bar of 20 mm in diameter. The chemical composition was Mg–3 mass%Al–0.95 mass%Zn–0.28 mass%Mn. Tensile specimens, machined directly from the extruded bar, had tensile axes parallel to the extruded direction. The specimens had a gauge length of 10 mm and diameter of 5 mm. Tensile tests were carried out at temperatures ranging from 623 to 723 K, and constant strain rates between 10^{-5} to 10^{-3} s^{-1} in air. The temperature variation during the tensile tests was not more than $\pm 1 \text{ K}$. Microstructures of the specimens were examined by optical microscopy. The average grain size d was measured by the liner intercept method using the equation $d = 1.74 L$, where L is the liner intercept size.⁶⁾ To study the deformation mechanism, the fracture surfaces were investigated by a scanning electron microscopy (SEM).

3. Results

A typical microstructure of the as-extruded material is shown in Fig. 1. The average grain size was about $37.5 \mu\text{m}$. As can be observed, the grains were almost equiaxed, and the grain size of the as-extruded Mg alloy was much larger than $10 \mu\text{m}$. Also, twinning was observed in the as-extruded Mg alloy, indicating that twinning deformation occurred during hot extrusion.

Figure 2 shows true stress-true strain curves at 673 K for strain rates ranging from 10^{-5} to 10^{-3} s^{-1} . At all strain rates, there was an immediate hardening upon loading, followed by an apparent softening. The true flow stress increased with strain up to a true strain of about 0.2. After the initial stage, the true stress decreased continuously with the increase of the true strain, and the strain softening was observed over a large range of strain of > 0.2 . However, superplastic metals that have fine-grained microstructure usually show apparent strain

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Fig. 1 A typical microstructure of the as-extruded Mg alloy.

Fig. 2 True stress-true strain curves at 673 K in the alloy.

hardening behavior. The apparent strain hardening behavior is often attributed to grain growth during superplastic deformation.¹³⁾ On the contrary, some superplastic alloys exhibit apparent strain softening behavior. The apparent strain softening behavior is often attributed to dynamic recrystallization during hot deformation.^{14–16)} In these alloys, grain refinement due to dynamic recrystallization is attained during an initial stage of tensile test. Therefore, the fact that the flow stress decreased with strain in a range of a true strain of > 0.2 , as shown in Fig. 2, suggests that dynamic recrystallization occurred during the tensile test in the as-extruded Mg alloy.

Microstructures of the specimens deformed to a true strain of 0.2 and 0.5 at 673 K and at strain rate of $3 \times 10^{-5} \text{ s}^{-1}$ are shown in Fig. 3. Changes in the microstructure were discernible even after a true strain of 0.2; the grain size of the specimen became $25 \mu\text{m}$ (Fig. 3(a)). In the case of a true strain of 0.5 (Fig. 3(b)), the mean grain size of the specimen was only $11 \mu\text{m}$, indicating that grain refinement was obtained during an initial stage of tensile test. Also, no twining was observed in the specimens. These facts show that recrystallization occurred dynamically during the tensile test.

The microstructure of the specimen deformed to failure at strain rate of $3 \times 10^{-5} \text{ s}^{-1}$ and at 673 K is shown in Fig. 4. It is observed the grain growth occurred apparently during the final stage of superplastic deformation. The average grain size of the specimen increased to $83 \mu\text{m}$. The morphology of the grains, however, is essentially unchanged and still equiaxed after superplastic deformation.

Fig. 3 Microstructures of the specimens deformed to true strains of (a) 0.2 and (b) 0.5 at 673 K and at $3 \times 10^{-5} \text{ s}^{-1}$.

Fig. 4 Microstructure of the specimen deformed to failure at 673 K and at $3 \times 10^{-5} \text{ s}^{-1}$.

In order to investigate the plastic flow behavior in the alloy, the flow stress as a function of strain rate is illustrated in Fig. 5(a). The flow stress for each strain rate was determined at a fixed strain of 0.15. The flow stress decreased with increasing temperature, and increased with strain rate. The strain rate sensitivity exponent, m , defined as the slope of a double logarithmic plot of flow stress vs. strain rate, exhibited a high

Fig. 5 Variation in (a) flow stress and (b) elongation-to-failure as a function of strain rate.

$$T=673 \text{ K}, \dot{\epsilon}=3 \times 10^{-5} \text{ s}^{-1}, \delta=314 \%$$

Fig. 6 Macrograph of the specimen deformed to failure at 673 K and $3 \times 10^{-5} \text{ s}^{-1}$.

value of about 0.4 at the strain rate ranges from $1 \times 10^{-3} \text{ s}^{-1}$ to $1 \times 10^{-5} \text{ s}^{-1}$.

Figure 5(b) demonstrates the elongation to failure as a function of strain rate. It is evident that the elongation to failure depends on the strain rate and temperature. The elongation to failure was higher when the specimen was deformed under higher strain rate sensitivity exponent of m , corresponding to that in Fig. 5(a). The maximum elongation to failure of 314% was obtained at the strain rate of $3 \times 10^{-5} \text{ s}^{-1}$ and at 673 K. Figure 6 showed a macrograph of the specimen deformed to failure in this condition. It is obvious that the deformed specimen is very uniform with no visible necking. It can be concluded that the test material exhibits good superplasticity in some proper conditions.

4. Discussion

It is accepted that grain boundary sliding (GBS) is the dominant deformation mechanism of superplastic deformation.^{16,17} When the superplastic deformation proceeds by GBS, grains remain equiaxed and failure occurs as a result of the growth and interlinkage of cavities formed on the grain boundaries.^{9,18} Figure 4 shows the main character of GBS. It revealed that grains were not elongated along the tensile direction even after large deformation ($\epsilon_f = 314\%$), and that cav-

Fig. 7 The fracture surface of the specimen deformed at 673 K and $3 \times 10^{-5} \text{ s}^{-1}$.

ities formed around the grain boundaries. These confirm that the GBS makes a substantial contribution to the total strain in the present alloy as well as in conventional superplastic materials. Figure 7 shows the fracture surface of the specimen deformed at the strain rate of $3 \times 10^{-5} \text{ s}^{-1}$ and at 673 K. It is clearly observed that the specimen was fractured intergranularly. The result also verifies that the GBS mechanism played a dominant role in the superplastic deformation of the studied alloy.

The current results reveal that grain refinement was obtained in the test alloy due to the dynamic recrystallization (Figs. 2, 3). Some researchers discovered that the dynamic recrystallization (DRX) occurs readily in magnesium and its alloys.^{17,19,20} Mwembela *et al.*²¹ showed that dynamic recrystallization occurred at 573 K in AZ31 ingot alloys during hot torsion testing. Watanabe *et al.*²² also revealed the dynamic recrystallization behavior in a commercial AZ31 alloy during upset forging. However few studies about the relationship between dynamic recrystallization and superplastic deformation in AZ31 magnesium alloys have been seen. As shown in Fig. 2, the dynamic strain softening behavior indicated that the origin of the dynamic recrystallization in the present alloy is continuous recrystallization.¹⁴⁻¹⁶ Microstructural evolution in continuous recrystallization is often the result of a combined precipitation/recrystallization reaction in some Zr or Sc bearing superplastic Al alloys.^{15,16} Yang *et al.*²³ showed that continuous recrystallization was stimulated by prior warm-deformation in an alloy. However, the

present experimental results revealed that continuous recrystallization occurred dynamically in the Mg–3Al–1Zn magnesium alloy which contained no fine and stable particles and was not warm-deformed prior to the tensile test. Therefore fine particles and prior warm-deformation are not needed to attain dynamically continuous recrystallization in the Mg alloy. Mohri *et al.*¹⁶⁾ also confirmed same results in a rolled Mg–9Al–1Zn alloy.

The dynamic recrystallization in magnesium alloys can refine grains and increase the large-angle grain boundaries, which are propitious for grain boundary sliding, and create appropriately microstructural prerequisites for superplastic deformation. Therefore, the studied alloy exhibited a higher elongation to failure and a higher strain rate sensitivity exponent. However, it should be pointed out that grain refinement occurred only during an initial stage of tensile test, up to a true strain of about 0.5, in the test alloy. After the true strain exceeded a certain value, the dynamic grain growth occurred in the alloy, which caused the failure of specimens (Fig. 4). Therefore, the dynamic recrystallization was merely an accommodated mechanism for the superplastic deformation.

5. Conclusions

The commercial magnesium alloy exhibited good superplasticity at the strain rates ranging from 10^{-5} to 10^{-3} s^{-1} and at temperatures ranging from 623 to 723 K. The strain rate sensitivity exponent of m was about 0.4 and the maximum elongation to failure reached to 314%.

Grain refinement was obtained in the test alloy due to the dynamic recrystallization during an initial stage of tensile test. The grain size of the as-extruded Mg alloy was $37.5 \mu\text{m}$. However, the grain size of the specimen deformed to a true strain of 0.5 at 673 K and at strain rate of $3 \times 10^{-5} \text{ s}^{-1}$ was $11 \mu\text{m}$.

Microstructural evidence and fracture surface analysis indicated that the superplastic deformation was mainly dominated by grain boundary sliding mechanism, and the dynamic recrystallization was an accommodated mechanism during the superplastic deformation.

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