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High strain rate superplasticity of rolled AZ91 magnesium alloy

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Abstract

The high strain rate superplastic deformation properties and characteristics of a rolled AZ91 magnesium alloy at temperatures ranging from 623 to 698 K (0.67T_m-0.76T_m) and high strain rates ranging from 10^{-3} to 1 s^{-1} were investigated. The rolled AZ91 magnesium alloy possesses excellent superplasticity with the maximum elongation of 455% at 623 K and a strain rate of 10^{-3} s^{-1}, and its strain rate sensitivity *m* is high up to 0.64. The dominant deformation mechanism responsible for the high strain rate superplasticity is still grain boundary sliding (GBS), and the dislocation creep mechanism is considered as the main accommodation mechanism.

Keywords: AZ91 magnesium alloy; high strain rate superplasticity; rolling; grain boundary sliding

1. Introduction

Recently, magnesium alloys have become one of the excellent promising light alloys employed widely in the automobile and electronic industries. The demand of magnesium alloys as structural materials is increasing significantly because of their low density, good damping characteristics and machinability. To increase the structural applications of magnesium alloys, the development of plastic forming technology such as rolling, forging, and press forming is desirable [1]. However, magnesium alloys are difficult to be formed directly due to their low ductility at room temperature [2]. It is therefore required to improve the poor workability of magnesium alloys for the development of plastic forming technology. Research on magnesium alloys has made rapid progress, with a series of achievements to its credit [3-8].

It is generally known that many alloys with grain sizes less than 10 μm can obtain excellent superplasticity under a lower strain rate ranging from 10^{-5} to 10^{-3} s^{-1} [9]. But a much lower strain rate will increase the forming time and limit their industrial applications. A strain rate higher than 10^{-3} s^{-1} can shorten the forming time, economize energy, and prevent high temperature oxidation of magnesium alloys [10-11]. However, little study was done on the higher strain rate superplasticity of magnesium alloys. Therefore, research on the high strain rate superplasticity of magnesium alloys will be emphasized in future.

Studies have shown that grain refining can significantly improve the superplasticity of alloys [12-13]. Rolled magnesium alloys can obtain fine grain sizes, but there are very limited data to understand the deformation characteristics and mechanisms of the rolled magnesium alloys at higher strain rates. Mohri studied the superplasticity of magnesium alloys at 573 K and a strain rate of 1.5×10^{-3} s^{-1}, which needs to be investigated further, though a number of conclusions are meaningful [14]. In the present study, the superplastic behavior of the rolled AZ91 magnesium alloy was systematically investigated at strain rates higher than 10^{-3} s^{-1}.

2. Experimental

The magnesium alloy used in the present investigation was Mg-9wt.%Al-0.8wt.%Zn-0.3wt.%Mn alloy. The magnesium alloy blocks with a thickness of 5.2 mm were cut from the ingot and solution-treated at 688 K for 7.2×10^4 s. The rollers were heated to 403 K prior to rolling, and the blocks were heated at 673 K for 1.8×10^3 s and then rolled with a reduction rate of 10%-20% per pass. The heating and rolling were repeated for 11 passes, and finally the blocks were rolled to a thickness of 1.5 mm. The total reduction

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rate in thickness was 71%.

Tensile specimens were machined directly from the as-rolled sheets with their tensile axes parallel to the rolling direction. The tensile specimens had a gauge length of 10 mm, a width of 5 mm, and a thickness of 1 mm. Constant velocity tensile tests were carried out at temperatures ranging from 623 to 698 K and at initial strain rates ranging from 10^{-3} to 1 s^{-1} in air. The specimens required 1.8×10^{3} s to equilibrate at the tested temperature prior to initiation of straining. The temperature variation during the tensile tests was not more than ±1 K.

Microstructures of the rolled AZ91 magnesium alloys before and after the tensile test were observed by optical microscopy. The average grain size *d* was measured by the liner intercept method, using the equation $d = 1.74L$, where *L* is the liner interception size. The fractured surfaces were investigated by scanning electron microscopy (SEM).

3. Results and discussion

Undeformed and fractured tensile specimens are shown in Fig. 1, where a uniform elongation of 455% is obtained at 623 K and 10^{-3} s^{-1}. The deformation is apparently relatively uniform and no visible necking took place around the fracture. Necking is apparently restrained during superplastic deformation [14].

The variation of flow stress at a fixed strain of 0.15 as a function of strain rate is plotted in Fig. 2. The strain of 0.15 is selected so that the occurrence of grain growth during initial superplastic flow stage is negligible [5]. It has been demonstrated that the flow stress increases with the increase in the strain rate and exhibited a typical sigmoidal curve in a manner similar to that observed previously in conventional superplastic materials. The strain rate sensitivity exponent, *m*, defined as the slope of the double logarithmic plot of flow stress versus strain rate, is measured to be about 0.64 in the intermediate strain rate range in the curve at 623 K. Generally, large elongations are obtained at the strain rate and temperature where high *m* values are found. The rolled AZ91 magnesium alloys studied have obtained the best superplastic elongation of 455% at a strain rate of 10^{-3} s^{-1} and at 623 K.

As demonstrated in Fig. 2, at strain rates ranging from 10^{-3} to 10^{-1} s^{-1}, the average high *m* value of about 0.5 is obtained. This high *m* value demonstrates that grain boundary sliding (GBS) can be a primary deformation mechanism in the rolled AZ91 magnesium alloys. Furthermore, the *m* value at high strain rate above 10^{-1} s^{-1} decreases to about 0.2, which may be due to the dislocation creep process associated with the much higher deformation rate [4]. Fig. 2 also shows that the flow stress decreases with increasing temperature, and the flow stress changes more greatly at higher strain rates than at lower strain rates.

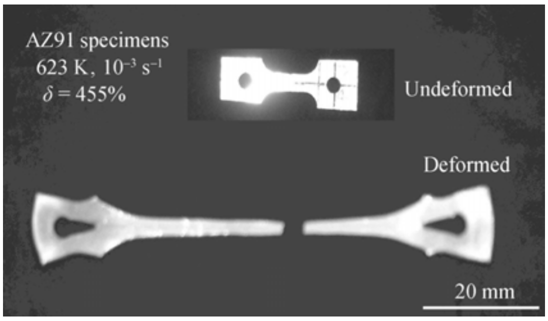

Fig. 1. Undeformed and fractured specimens of AZ91.

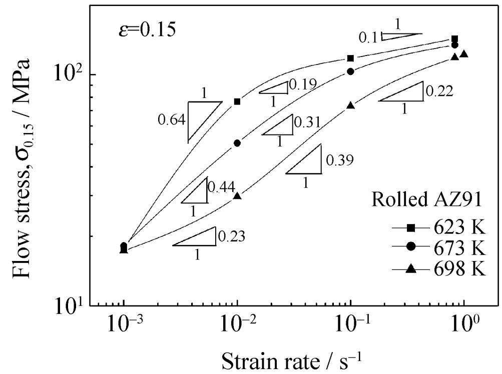

Fig. 2. Variation of flow stress as a function of strain rate.

To understand the mechanism involved in the superplastic process, the superplastic deformation activation energy *Q* is calculated under constant strain rates by the following equation [17]:

$$Q = NR\frac{\partial(\ln\sigma)}{\partial(1/T)} \tag{1}$$

where σ is the flow stress, *N* is the stress exponent ($N = 1/m$), *R* is the gas constant (R = 8.314 J/K), *T* is the thermodynamic temperature, and $\partial(\ln\sigma)/\partial(1/T)$ is estimated from the slopes of the curves in Fig. 3. It is demonstrated in Fig. 3 that the slopes of the curves increase with an increase in temperature and change with strain rates. The activation energy for the superplastic deformation of the rolled AZ91 alloy determined by Eq. (1) is from 93 to 238 kJ·mol^{-1}, which is much higher than the activation energy for lattice diffusion (134 kJ·mol^{-1}) or grain boundary self-diffusion (75 kJ·mol^{-1}) of the magnesium alloys, respectively [15]. It is suggested that when the strain rate and temperature are high, the dislocation creep requiring higher activation energy [8] may effectively accommodate grain boundary sliding during the superplastic deformation process.

The typical microstructures of the rolled AZ91 magnesium alloys before and after the tensile test are shown in Figs. 4(a) and 4(b). Both of them are perpendicular to the tensile direction. As demonstrated in Fig.4 (a), the grains are

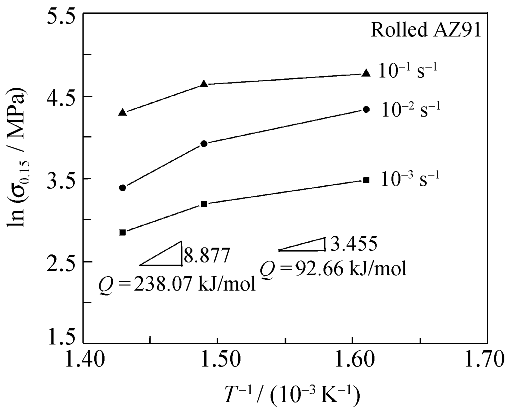

Fig. 3. Active energy curves of ln $\sigma_{0.15}$ versus 1/*T* in the rolled AZ91 superplastic deformation.

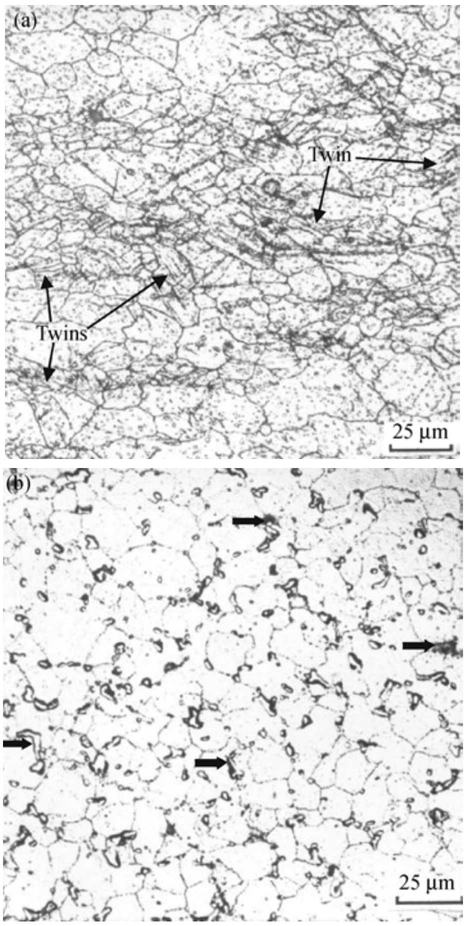

Fig. 4. Typical microstructures of the rolled AZ91 magnesium alloys before (a) and after (b) the tensile test with the maximum elongation of 455% (623 K, 10^{-3} s^{-1}).

almost equiaxed. The average grain size is measured to be about 11 μm. Thus this material fulfills the structural prerequisites for superplastic deformation [14]. At the same time, there apparently exist lots of twins after rolling.

As shown in Fig. 4(b), the grain growth took place during the superplastic deformation and no twins could be observed after large superplastic deformation. This indicates that dynamic recrystallization occurs during the superplastic deformation process [14], and the average grain size increases to about 16 μm. Although a few grains have elongated traces along the tensile direction, most of the grains are still nearly equiaxed. Besides, some small grains have slid-traces along large grains' boundaries. This indicated that grain boundary sliding (GBS) makes a substantial contribution to the total strain in the present AZ91 alloy at high strain rates as in conventional superplastic materials. And the elongated cavities can be observed between the grain boundaries (stated as arrows), which are typical for superplastic deformation.

It is accepted that grain boundary sliding is the dominant deformation process of superplastic flow; therefore the surfaces of the deformed specimens are observed to reveal grain boundary sliding [16-17]. This is further observed clearly in Fig. 5, which shows surface microstructures in the superplastic deformation section parallel to the tensile direction of rolled AZ91. It is clearly observed in Fig. 5 that many of the equiaxed grains distributes homogeneously through the superplastic deformation section; besides, there are a number of cavities around much thicker grain boundaries, and there also exist lots of refined interspaces with an average width of 1 mm between the grain boundaries (stated by arrows). These results indicate that grain boundaries are high-angle boundaries and grain boundary sliding (GBS) that occurs significantly [16].

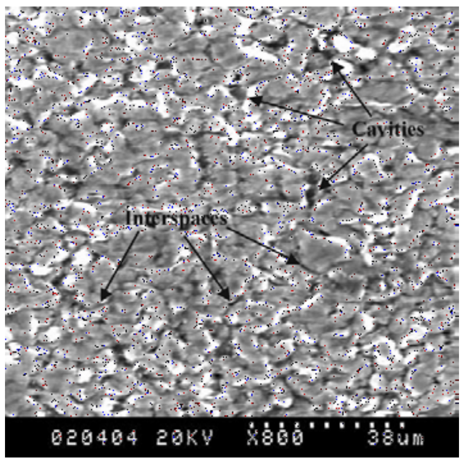

Fig. 5. Fracture surface of the rolled AZ91 after the best superplastic deformation.

These microstructure results indicate that the main superplastic deformation mechanism in the rolled AZ91 magnesium alloys at high strain rates is still grain boundary sliding (GBS), which is similar to the superplastic deformation at low strain rates. But compared with the superplastic deformation at low strain rates, the main accommodation mechanism of grain boundary sliding (GBS) is the dislocation creep mechanism.

4. Conclusions

The superplasticity of a rolled AZ91 magnesium alloy was investigated at high strain rates ranging from 10^{-3} to 1 s^{-1} and at temperatures ranging from 623 to 698 K. The results are summarized as follows:

(1) The present alloy exhibits excellent superplasticity at high strain rates. The maximum superplastic tensile elongation of 455% is obtained at a strain rate of 10^{-3} s^{-1} and at 623 K, corresponding to the high strain rate sensitivity exponent *m* of 0.64.

(2) Dynamic recrystallization occurs and grain growth takes place in the rolled AZ91 magnesium alloy during the superplastic deformation process.

(3) The microstructure evidence indicates that the dominant deformation mechanism in high strain rate superplasticity is still grain boundary sliding (GBS) mainly accommodated by the dislocation creep process.

Acknowledgement

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