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Shear punch superplasticity in equal-channel angularly pressed Mg–12Li–1Zn alloy

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ABSTRACT

The superplasticity of a fine-grained Mg–12Li–1Zn alloy, processed by equal-channel angular pressing (ECAP), was studied by shear punch testing. The strain rate sensitivity index of 0.45 and activation energy of 71 kJ mol^{-1} is indicative of a superplastic shear behavior dominated by grain boundary sliding.

1. Introduction

The superplasticity of materials relies primarily on the small size of the grains, preferably of high-angle type [1]. Among many possible means of attaining such fine structures, severe plastic deformation techniques including processing by equal-channel angular pressing (ECAP) have attracted special attention [2,3]. The ECAP method is a promising technique capable of producing fine-grained microstructures suitable for superplastic deformation of magnesium alloys [4,5]. In this process, a billet is pressed repetitively through an angular die, to undergo a very high shear strain without any change in the cross-sectional area, the principles of which have been reviewed by Valiev and Langdon [6]. Despite the great attention paid to the superplastic behavior of the ECAPed Mg alloys [7], only a few studies have been performed on the Mg–Li alloys [8]. Most of these studies have mainly concentrated on the determination of superplasticity by the conventional tensile methods. The Mg–Li alloy with Li content greater than 11 wt% exhibits a single bcc β phase structure. This structure is expected to provide more slip systems and higher ductility values, as compared to the hcp-structured Mg–Li alloys with lower Li contents. Therefore, it would be of interest to evaluate the superplasticity of bcc-structured Mg–Li alloys.

Shear punch test (SPT) is a miniature testing technique, which has been recently used for evaluating strength properties of both cast [9] and wrought [10,11] magnesium alloys. In this test, mechanical properties such as shear yield stress (SYS), ultimate shear strength (USS) and shear elongation values can be obtained by plotting shear stress against normalized displacement. SPT has not previously been used for evaluating superplastic behavior of any Mg alloy through determination of the parameters commonly considered as characteristics of superplasticity. One of these parameters is the strain-rate sensitivity (SRS) index (m), which can be used to assess the superplastic behavior. It is therefore the aim of the present study to characterize the superplastic shear behavior of a fine-grained Mg–12%Li–1%Zn alloy in the temperature range 473–548 K ($T > 0.5\,T_m$), by measuring the SRS indices and activation energies. It is also intended to evaluate deformation mechanisms of the alloys having various grain sizes, obtained by conventional extrusion and by ECAP.

2. Experimental procedure

The material used was an Mg–Li–Zn (LZ121) alloy containing 11.8 wt% Li and 0.8 wt% Zn. Extrusion was carried out with an extrusion ratio of 11:1 at 573 K. Pressing of the extruded billets was conducted at 473 K using a solid die with channel angles of $\varphi = 90^\circ$ and $\psi = 20^\circ$. Samples were pressed at a speed of 1 mm s^{-1} for two passes through the die using route B_C.

One-millimeter thick slices were cut from the extruded and ECAPed bars perpendicular to the pressing direction and ground to a thickness of about 0.7 mm. Shear punch tests were conducted in the temperature range 473–548 K and shear strain rate range 0.001–0.060 s^{-1}, using a SANTAM universal testing machine. A shear punch fixture with a 3.175 mm diameter flat cylindrical punch and a 3.225 mm diameter receiving-hole was used. The assembly of the specimen and fixture were accommodated by the split furnace, and held for 15 min to establish thermal equilibrium

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in the testing arrangement. The applied load P was measured automatically as a function of punch displacement; the data were acquired by a computer so as to determine the shear stress using the relationship [12]

$$\tau = \frac{P}{\pi d t} \tag{1}$$

where P is the punch load, t is the specimen thickness and d is the average of the punch and die diameters. The microstructure of the materials was revealed by optical microscopy, and average grain sizes of 8 and 48 μm were measured for the ECAPed and extruded conditions, respectively.

3. Results and discussion

Typical SPT curves, plotted as shear stress (τ) against normalized punch displacement ($\delta = h/t$, where h is the displacement), are shown for both ECAPed and extruded materials at different shear strain rates in Fig. 1. The shear strain rates were calculated using the following equation [12]:

$$\dot{\gamma} = \frac{1}{2}\frac{\dot{Z}}{W} \tag{2}$$

where $\dot{Z}$ is the punch-displacement rate and W is the die-punch clearance. As can be seen, similar to conventional superplastic tensile curves, after elastic region and a rather short strain hardening stage, almost all of the SPT curves show a relatively long strain softening region, which moves toward a near steady-state region in the ECAPed condition. It is also evident that the flow stress of the alloy significantly increases with increasing strain rate in both conditions, indicating the positive strain rate sensitivity of the material at high temperatures [1].

It is generally accepted that the high-temperature flow stress (σ) of superplastic materials can be related to the strain rate ($\dot{\varepsilon}$) by a power-law relationship

$$\dot{\varepsilon} = A\sigma^{1/m}\exp(-Q/RT) \tag{3}$$

where A is a material parameter, m denotes SRS index, Q is the deformation activation energy, R is the universal gas constant and T is the temperature. σ can be either yield stress or peak stress. This equation can be simply modified for evaluating superplastic behavior in the SPT method by replacing $\dot{\varepsilon}$ with $\dot{\gamma}$ and σ with τ. This can be conducted using the Von Mises criterion for a state of pure shear of kinematically hardening materials, which presents $\sigma = \sqrt{3}\tau$ and $\varepsilon = (1/\sqrt{3})\gamma$. Therefore, the modified form of Eq. (3) can be rewritten in the form of

$$\dot{\gamma} = A_1\tau^{1/m}\exp(-Q/RT) \tag{4}$$

where $\dot{\gamma}$ is shear strain rate and $A1$ is a material parameter. Due to the constancy of Q at a given temperature, it is possible to determine the SRS index (m) from

$$m = \left(\frac{\partial \ln \tau}{\partial \ln \dot{\gamma}}\right)_T \tag{5}$$

The above equation has been successfully used for Cu [13] and Sn–Sb [14] alloys. The SRS index of 0.57 obtained by SPT of fine-grained ECAPed Sn–5Sb alloy is in a good agreement with $m = 0.60$ measured by the impression technique of the same material [1].

The calculation of activation energy can be done by rearranging Eq. (4) and differentiating with respect to $1/T$ to obtain a relationship of the form

$$Q = nR\left[\frac{\partial \ln \tau}{\partial (1/T)}\right]_{\dot{\gamma}} \tag{6}$$

where n is the stress exponent, which is equivalent to $1/m$.

To determine SRS index, the shear yield stress was plotted on a double-logarithmic scale against the shear strain rate at test temperatures of 473, 498, 523 and, 548 K, as depicted in Fig. 2a

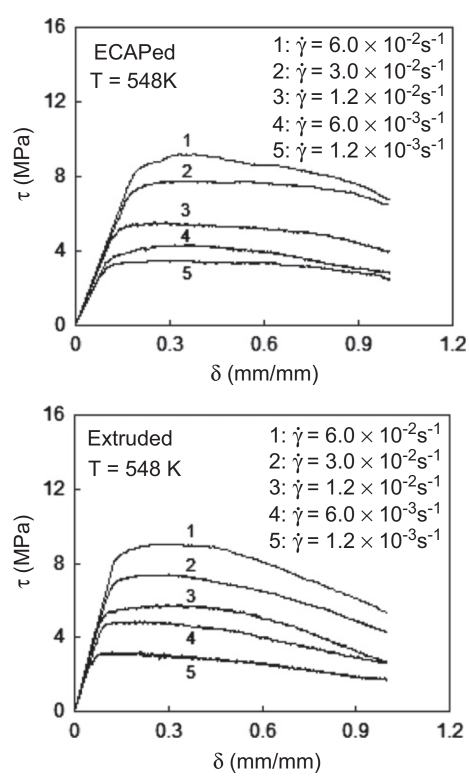

Fig. 1. SPT curves of the material obtained at different strain rates and $T = 548$ K.

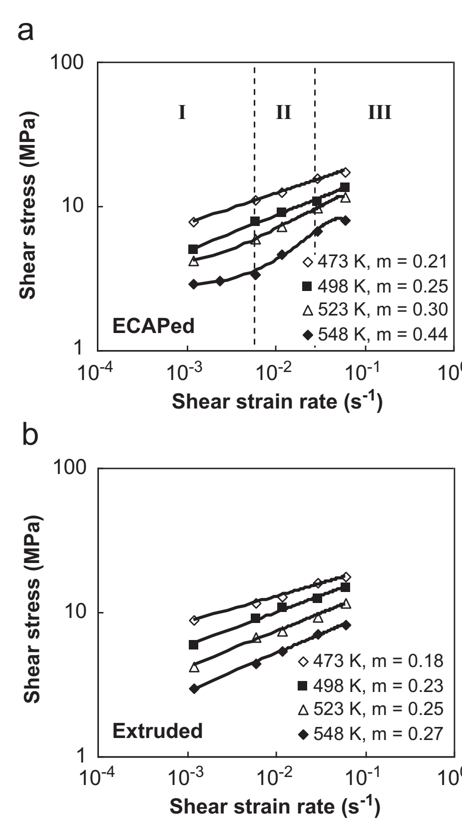

Fig. 2. Shear stress as a function of shear strain rate for (a) ECAPed, and (b) extruded conditions at various temperatures.