Ultrahigh Superplastic Elongations in an Aluminum–Lithium Alloy

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Alloys of the Al–Li–Mg system are known to exhibit low technological plasticity [1]. An effective method of fabricating products from such alloys is superplastic deformation [1]. The grain refinement in alloys of the Al–Li–Mg system as a result of the thermomechanical processing provides high superplasticity parameters [2]. In recent years, several investigations have been reported [3–7] in which a submicrocrystalline structure was obtained by the method of equal-channel angular pressing (ECAP), in which the maximum superplastic elongations amounted to 1850% [7]. The ECAP technology provides the manufacture of rods. At the same time, the necessary semiproducts for superplastic molding are sheets.

Previously, a method had been developed [8] for manufacturing sheets with a submicrocrystalline structure, which is based on the equal-channel angular extrusion (ECAE) via rectangular channels with subsequent isothermal rolling, the temperatures of both operations being close or identical. This paper presents data showing that the use of this method for processing aluminum alloy 1421 enabled us to achieve record high superplastic elongations.

Alloy 1421 with the chemical composition Al–5.1 wt % Mg–2.1 wt % Li–0.1 wt % Sc–0.08 wt % Zr was obtained by means of semicontinuous casting and homogenized at 425°C for 12 h. Then, it was repressed in the temperature range of 360–396°C with a degree of reduction about 60%. The ECAP was carried out at a temperature of 325°C to a true imposed strain of about 8. The blank of 125 × 125 × 25 mm in size was rotated through an angle of 180° around the exit-channel axis after each pass (route C_x [9]). This blank was used to cut samples of 115 × 115 × 15 mm in size, which were heated to a temperature of 325°C and rolled under isothermal conditions in working rolls heated to the same temperature. During the isothermal rolling (IR), the thickness of samples decreased from 15 to 1.8 mm for 8 passes that enabled us to obtain the total degree of reduction of about 88%. The methods of mechanical testing and structural analysis using electron backscattering diffraction are described in detail elsewhere [8, 10].

The combination of the ECAP with subsequent IR ensures the formation of a completely homogeneous recrystallized microstructure (Fig. 1) with an average grain size of 1.6 μm. The fraction of true grains surrounded with high-angle grain boundaries (HAGBs) reaches 51%, and the volume fraction of HAGBs amounts to 85% (see inset to Fig. 1).

Alloy 1421 with such a structure demonstrated extraordinary elongations (> 1000%) in a wide range of temperatures and strain rates (Figs. 2, 3). The maxi-

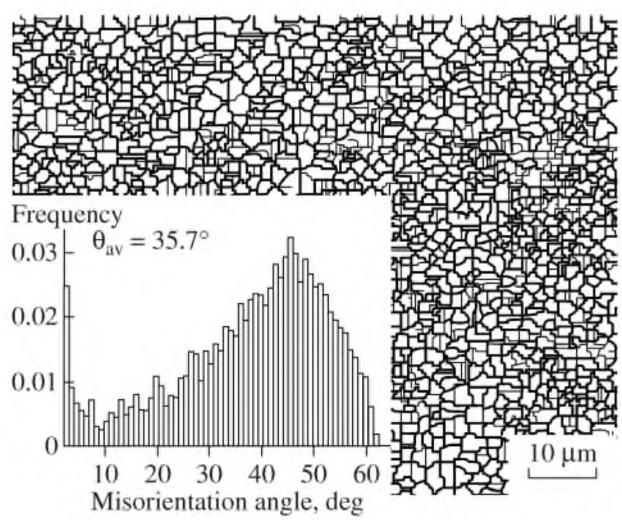

Fig. 1. Microstructure of alloy 1421 after the ECAP with subsequent IR stage.

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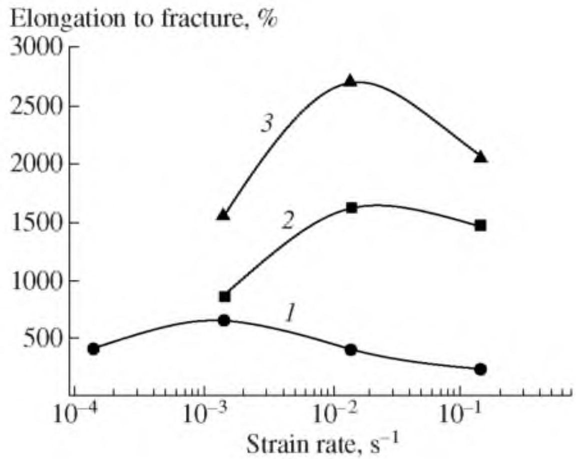

Fig. 2. Effect of strain rate on the elongation to fracture at (*1*) 300°C, (*2*) 400°C, and (*3*) 450°C.

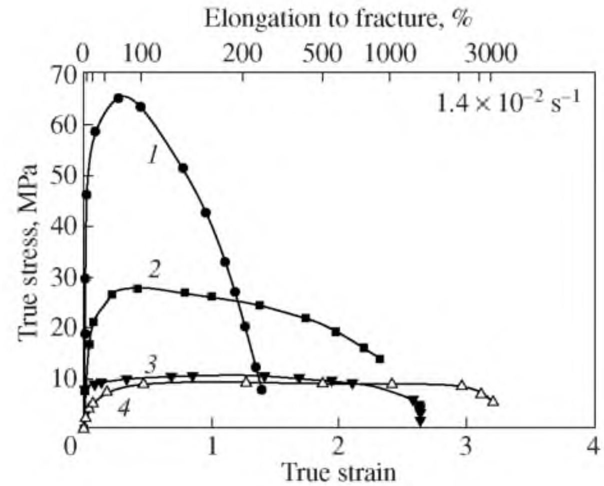

Fig. 3. Plots of the true stress versus imposed strain at (*1*) 300°C, (*2*) 400°C, (*3*) 450°C, and (*4*) 450°C.

mum relative elongation of 2700% was observed at 450°C and $\dot{\varepsilon} = 1.4 \times 10^{-2}$ s^{-1}. An analysis of the curves of the relative elongation versus strain rate at various temperatures (Fig. 2), on which three characteristic regions are clearly distinguished [11, 12], shows unambiguous evidence for the superplastic nature of the observed behavior. An increase in the temperature leads to a shift of the optimum interval of strain rates with respect to superplasticity [11, 12] toward higher strain rates, whereby the strain rate-sensitivity factor m increases from 0.32 at 300°C to 0.57 at 450°C (Fig. 3). Since the strain rates at which the superhigh relative elongations and the values of $m \geq 0.33$ are observed exceed 10^{-2} s^{-1}, it is possible to ascertain that the high-strain-rate superplasticity takes place. It is interesting to note that the relative elongation in the given alloy 1421 is much higher than in the same alloy subjected only to the ECAP treatment, in which the relative elongation of 1000% is observed for the same temperature and deformation rate [7, 10]. Hence, it is the isothermal rolling after the ECAP stage that provides an additional increase in the superplasticity characteristics.

The superplastic flow exhibits a strongly pronounced stationary stage (Fig. 3), in which the rate-sensitivity factor m at 450°C and $\dot{\varepsilon} = 1.4 \times 10^{-2}$ s^{-1} increases with the degree of straining from 0.5 for $e = 0.5$ to 0.6 for $e = 2$. Further deformation leads to a decrease in m; however, this value does not fall below 0.4. Thus, the high plasticity of the material is caused by high strain-rate sensitivity of the flow stresses, which prevents the strain localization with the formation of a neck and a weak pore formation.

Figure 4 shows an image of the fracture surface after the maximum elongation (~2700%). It can be seen that two types of pores are formed as in conventional superplastic materials [6–11]. However, in the given alloy 1421, fine equiaxial pores of the diffusion nature (not typical of the superplastic flow) predominate, especially for the strain rate above 10^{-2} s^{-1}. The amount of pores with an irregular shape of the deformation nature is relatively insignificant. The quasi-brittle fracture [11] limiting the plasticity of the material takes place because of the formation of bridges between large pores after straining to superhigh degrees (Fig. 4). This character of pore formation, which is not typical of the superplasticity in conventional materials, may be caused only by complete accommodation of the grain-boundary sliding, which prevents the formation of pores of the deformation nature as a result of the displacement of grains relative to each other and leads to their collapse during the superplastic flow. Thus, it is the suppression of the deformation-induced pore formation that provides for the achievement of ultrahigh elongations.

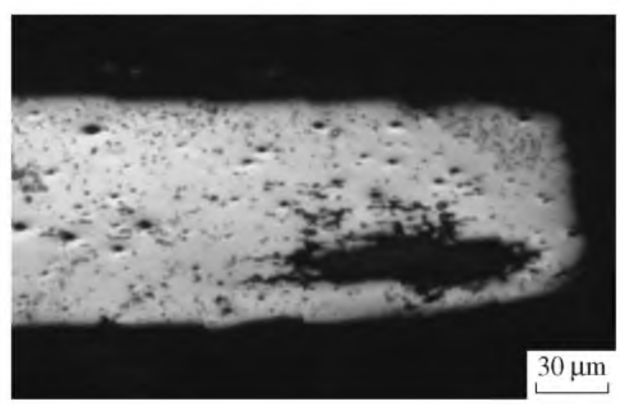

Fig. 4. The pattern of pore formation in a sample after the ECAP with subsequent IR upon the tensile test at a temperature of 450°C and a strain rate of 1.4×10^{-2} s^{-1}.

The cause of ultrahigh elongations in the given alloy 1421 is the formation of a homogeneous microstructure [8] during the ECAP treatment and the subsequent IR stage. The structure of equiaxial grains provides for the accommodation of the grain-boundary sliding [11, 12]. The pores of the deformation nature are formed in a negligible amount, and the material withstands ultrahigh elongations without fracture. In the alloys with nonuniform structure [11], the accommodation conditions for the grain-boundary sliding are worse and the formation of pores of the deformation nature results in premature fracture.

Thus, we showed that, in order to achieve the best superplasticity characteristics for alloys of the Al–Li system, the structural uniformity is of importance, provided that the grain size is within 0.5–2.5 μm. Alloy 1421 with such a structure shows the highest possible values of the strain rate-sensitivity factor for a flow stress of 0.5–0.6. Under these conditions, the fracture onset and the achievable relative elongation values depend exclusively on the formation of pores of the deformation nature. The formation of a homogeneous structure with equiaxial grains suppresses this type of pore formation. Such a structure is formed during thermomechanical processing consisting of the ECAP with the subsequent IR stage. Using this technological scheme, it is possible to manufacture thin sheets from alloys of the Al–Li system with record high superplasticity characteristics.

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