

Superplastic Response of an Advanced Al–Li–Mg–Cu–Sc Alloy Subjected to Intense Plastic Deformation

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A novel commercial Al–Li–Mg–Cu–Sc alloy was fabricated by casting and subjected to intense plastic deformation through equal-channel angular extrusion at 598 K to a total strain of ~ 16 . Superplastic properties of this alloy were studied in the temperature range of 623–773 K and at strain rates of 1.4×10^{-3} – $1.4 \times 10^{-1} \text{ s}^{-1}$. The highest elongation-to-failure of 650% appeared at 723 K and a strain rate of $1.4 \times 10^{-3} \text{ s}^{-1}$ with corresponding coefficient of strain rate sensitivity of 0.42. The microstructure evolution and cavitation during superplastic deformation were examined.

Keywords: aluminium alloy, equal-channel angular extrusion, superplastic deformation, microstructure, cavitation

1. Introduction

A novel commercial aluminum–lithium alloy, designated in Russia as 1443 aluminum alloy and denoted as 1443 Al herein, is an advanced aerospace material belonging to Al–Li–Mg–Cu–Sc system.¹⁾ The alloys of this system have the optimal combination of strength and crack propagation resistance.^{1,2)} Achievement of superplasticity in the 1443 Al will allow developing a superior high-strength aluminum alloy which can be superplastically formed into complex aerospace components. It is known^{3,4)} that aluminum alloys having grain sizes less than 10 μm are capable of achieving high superplastic properties. Therefore, the development of processing method for introducing considerable refinement into bulk billets of the 1443 Al is highly attractive for subsequent forming operations. In addition, there exists a unique effect of grain size on fracture toughness and crack propagation resistance under fatigue loading in Al–Li–Mg–Cu alloys.⁵⁾ The formation of recrystallized structure enhances characteristics of crack propagation resistance. It is expected that the superplastic 1443 Al with fine grained structure will exhibit enhanced workability, increased stress intensity factor, K_{Ic} , and decreased fatigue crack growth rate, as well.

It was recently shown^{6–8)} that equal-channel angular extrusion (ECAE) is capable of producing a significant grain refinement in commercial scale rods of aluminum alloys due to occurrence of dynamic recrystallization during intense plastic straining by simple shear. Aluminum alloys subjected to ECAE with large strains could exhibit high superplastic properties.^{7,8)} Thus, the aim of present study is to achieve superplasticity in the bulk samples of the 1443 Al using ECAE processing.

2. Experimental Procedure

The 1443 Al with a chemical composition of Al–1.9Li–1.0Mg–1.7Cu–0.03Sc–0.08Zr (in mass %) was manufactured

by direct chill casting followed by solution treatment at 803 K for 20 hours. Then it was cut into cylinders³ with 20 mm in diameter and 100 mm in length.

The ECAE of cylinders was performed using an isothermal die with a circular internal cross-section at a temperature of 598 K to the total true strain of ~ 16 by route B_C.⁹⁾ Details of ECAE procedure were reported previously.⁸⁾

Tensile specimens were cut parallel to the longitudinal axis of the pressed rods with a gauge length of 6 mm and cross-section of $3 \times 2 \text{ mm}^2$. These samples were pulled in tension to failure in air using a Shimadzu AG-G universal testing machine. Tension tests were carried out in the temperature interval 623–773 K at strain rates ranging from 1.4×10^{-3} to $1.4 \times 10^{-1} \text{ s}^{-1}$. Each sample was held at the testing temperature for about 20 min in order to reach thermal equilibrium. The strain rate sensitivity coefficient, m , was determined from the slope of the $\log \sigma$ vs. $\log \dot{\epsilon}$ curves.

Microstructure analysis was carried out using an optical microscope Olympus BX-60 and a transmission electron microscope Hitachi H-650 operating at an accelerating voltage of 200 kV. Grain boundary misorientation distributions were obtained from electron backscattering diffraction pattern (EBSP) using JEOL JXA8100 electron probe micro-analyzer with OIM software provided by TexSEM Lab., Inc.

3. Results and Discussion

A typical TEM structure of the ECAE processed 1443 Al and the grain boundary misorientation map obtained by EBSP analysis are shown in Fig. 1. One can see that ECAE at 598 K to a strain of 16 resulted in the formation of partially recrystallized structure. Fine recrystallized grains with sizes of 1–5 μm (Fig. 1(a)) alternated with unrecrystallized areas containing recovered subgrains. EBSP analysis showed that the volume recrystallized fraction was 70–75% and about 40% of grain boundaries had low-angle misorientations (Fig. 1(b)).

The tensile deformation curves of the 1443 Al at temperatures of 623–773 K and an initial strain rate of $1.4 \times 10^{-2} \text{ s}^{-1}$ are given in Fig. 2. Intensive strain hardening at the

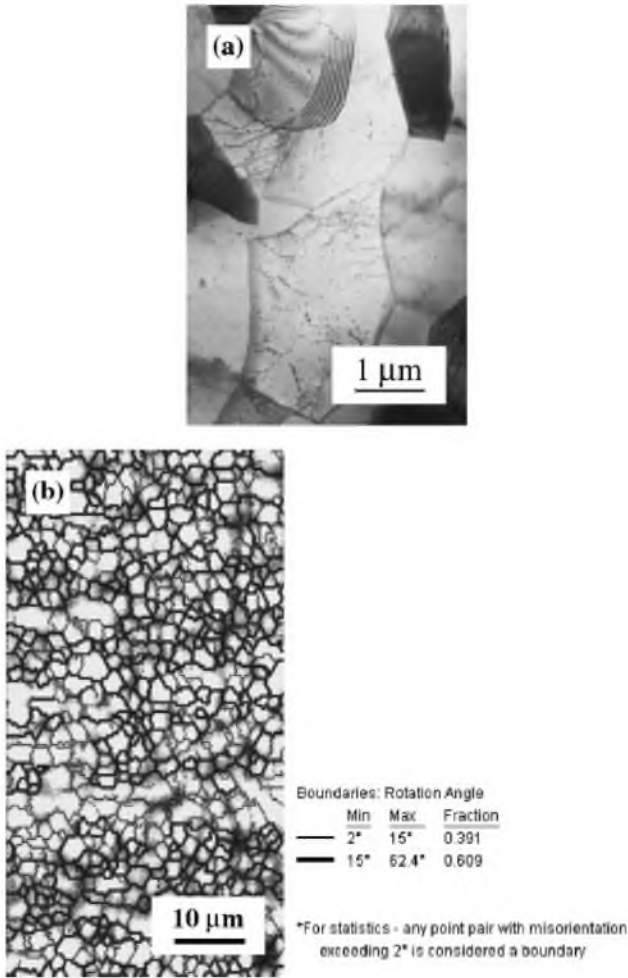


Fig. 1 Typical microstructure of the 1443 Al subjected to ECAE at 598 K: (a) TEM; (b) grain boundary misorientation map.

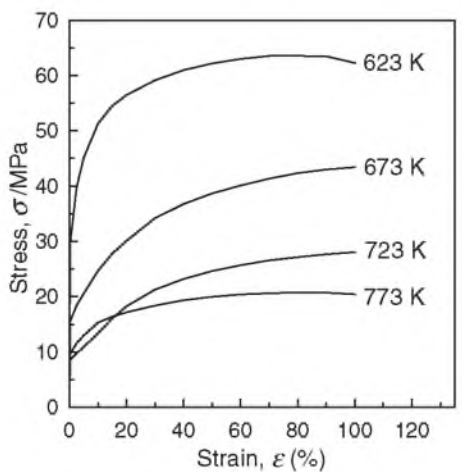


Fig. 2 Stress-strain curves of the 1443 Al at 623–773 K and an initial strain rate of $1.4 \times 10^{-2} \text{ s}^{-1}$.

beginning of deformation (particularly at 623 and 673 K) was followed by steady-state flow stage. A transition from strain hardening to steady-state flow is associated with an increase in the fraction of high-angle grain boundaries that facilitates grain boundary sliding. The steady state flow stress decreased continuously from 60 to 20 MPa when the testing temperature was increased from 623 to 773 K.

Figure 3 presents the temperature dependence of the total elongation at a strain rate of $1.4 \times 10^{-2} \text{ s}^{-1}$. Increase in the testing temperature led to appearance of a well-defined elongation maximum of 420% at 723 K indicating a high strain rate superplasticity in the 1443 Al. Marginal superplastic elongations were observed both at higher and lower temperatures at that high strain rate.

The strain rate dependence of the total elongation at 723 K is shown in Fig. 4(a). The elongation tended to increase with decreasing strain rate and reached the maximum of 650% at

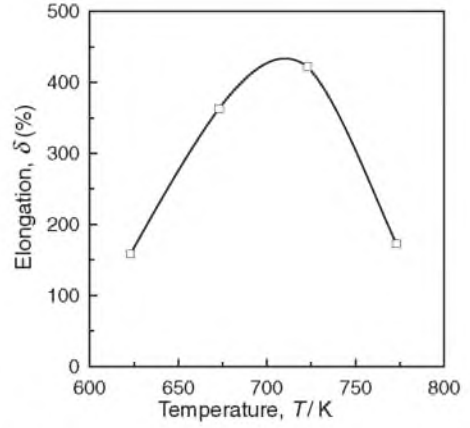


Fig. 3 Temperature dependence of total elongation of the 1443 Al. Initial strain rate was $1.4 \times 10^{-2} \text{ s}^{-1}$.

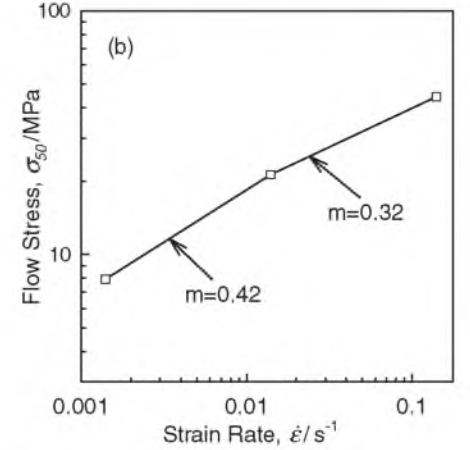
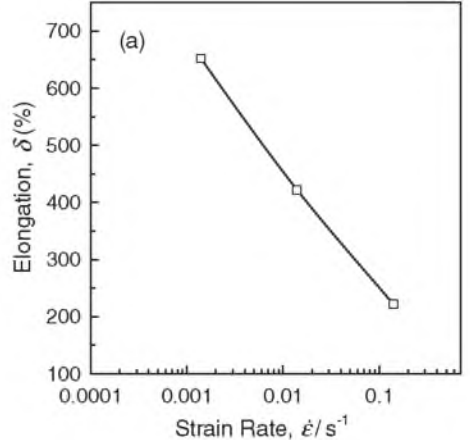


Fig. 4 Strain rate dependencies of (a) total elongation and (b) flow stress σ_{50} of the 1443 Al at 723 K.

$$\dot{\epsilon} = 1.4 \times 10^{-3} \text{ s}^{-1}.$$

Figure 4(b) gives a plot of the flow stress taken at $\epsilon = 50\%$ as a function of initial strain rate at 723 K in a double logarithmic scale. The steady-state flow stress value increased monotonically with decreasing strain rate. No well-defined sigmoidal shape of the stress-strain rate curve, as in the case of typical superplastic alloys,^{3,4)} appeared in the 1443 Al at 723 K. The strain rate sensitivity coefficient, m , higher than 0.3 was observed in all the strain rate range examined (Fig. 4(b)). The higher values of strain rate sensitivity, $m = 0.42$ were obtained at lower strain rates (Fig. 4(b)) that corresponded to ductility maximum (Fig. 4(a)).

OM analysis of deformed samples revealed that, in general, non-uniformity of structure evolved during ECAE remained under static annealing in grip section of samples pulled to failure (Fig. 5(a)). The initial grains are essentially stable under static annealing even at $T \geq 723$ K. No remarkable static growth of recrystallized grains was found. In contrast, superplastic deformation resulted in significant microstructural evolution that can be associated with dynamic recrystallization (Fig. 5(b)). Superplastic deformation increased homogeneity of microstructure via eliminating coarse unrecrystallized grains. Two types of grains could be distinguished in superplastically deformed samples (Fig. 5(b)). First structural component was recrystallized grains with elongated shape and average size of about $8 \mu\text{m}$. Those grains dominated. Second structural component was very fine grains ($\sim 2\text{--}3 \mu\text{m}$) with equiaxed shape. Notably, microstructure evolved after superplastic deformation was essentially homogeneous on macroscale level. In all areas of

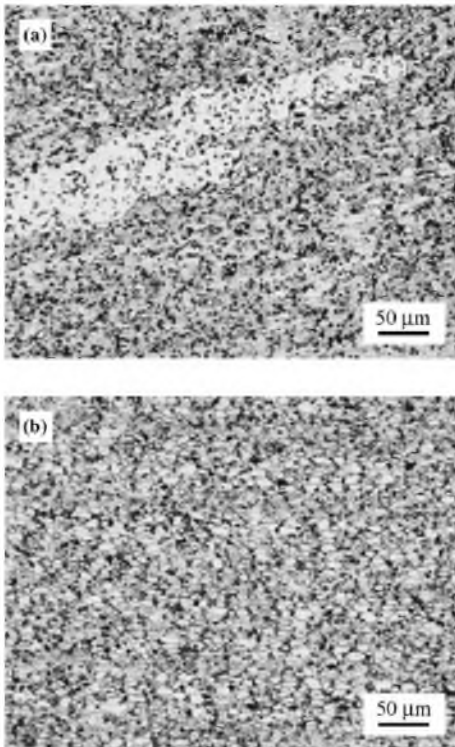


Fig. 5 OM photomicrographs of (a) grip and (b) gauge sections of the 1443 Al sample after tensile testing ($T = 723$ K; $\dot{\epsilon} = 1.4 \times 10^{-2} \text{ s}^{-1}$; $\delta = 420\%$).

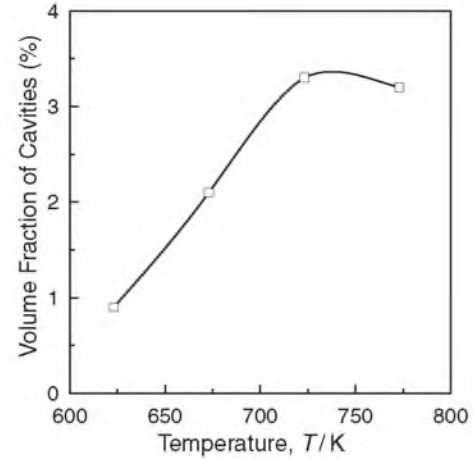


Fig. 6 Volume fraction of cavities near the fracture zone vs. testing temperature in the 1443 Al at a strain rate of $1.4 \times 10^{-2} \text{ s}^{-1}$.

tensioned samples the very fine equiaxed grains alternated with coarse grains with elongated shape. Thus, it is obvious that the 1443 Al is capable of superplastic deformation in partially recrystallized condition as the other alloy belonging to the similar system.¹⁰⁾ Dispersion particles prevent static recrystallization of warm worked 1443 Al, and superplastic deformation induces high-angle boundaries via continuous dynamic recrystallization.¹¹⁾

Analysis of the cavitation near the fracture zone revealed the common tendency: it increased both with increasing the testing temperature and the total elongation. The plot of the volume fraction of cavities near the fracture zone vs. testing temperature in the 1443 Al at a strain rate of $1.4 \times 10^{-2} \text{ s}^{-1}$ is shown on Fig. 6. One can see that the volume fraction of cavities was less than 3.5% (Fig. 6) even at 723 K when the elongation of 420% was obtained (Fig. 3). It seems to be caused by increasing the homogeneity of microstructure in the ECAE processed material during superplastic deformation.

Thus, the results of the present study showed that ECAE is an effective route to produce fine-grained microstructure in the 1443 Al. The ECAE processed 1443 Al exhibits high ductility of 650% at essentially the same temperature and strain rate range as Supral (Al-6%Cu-0.5%Zr) alloy which is classic superplastic material.⁴⁾ At the same time, in order to produce the fully recrystallized microcrystalline structure and to improve the superplastic properties of the 1443 Al, the ECAE regimes have to be optimized.

4. Conclusions

- (1) Equal-channel angular extrusion of the 1443 Al at 598 K to a total strain of 16 resulted in the formation of partially (about 70–75%) recrystallized microstructure with the mean size of recrystallized grains of $4 \mu\text{m}$.
- (2) Superplastic properties of the 1443 Al were studied in the temperature range of 623–773 K and at strain rates of 1.4×10^{-3} – $1.4 \times 10^{-1} \text{ s}^{-1}$. The highest elongation-to-failure of 650% appeared at 723 K and a strain rate of $1.4 \times 10^{-3} \text{ s}^{-1}$ with corresponding coefficient of strain rate sensitivity of 0.42.

- (3) Superplastic deformation led to considerable improvement of microstructure homogeneity suggesting an occurrence of dynamic recrystallization within initial unrecrystallized areas.

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