Achieving Superplasticity in the 7055 Aluminum Alloy

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Keywords: aluminum alloy, equal channel angular extrusion, superplastic deformation.

Abstract. Superplasticity in a 7055 aluminum alloy subjected to intense plastic straining through equal-channel angular extrusion (ECAE) was studied in tension over a range of strain rates from 1.4×10^{-5} to 5.6×10^{-2} s^{-1} in the temperature interval 300-450°C. The alloy had a grain size of ~1 μm. A maximum elongation-to-failure of ~750% appeared at a temperature of 425°C and an initial strain rate of 5.6×10^{-4} s^{-1}, where the strain rate sensitivity coefficient, m, was about 0.46. The highest m value was ~0.5 at a strain rate of 1.4×10^{-3} s^{-1} and T≥425°C. Moderate superplastic properties with a total elongation of about 435% and m of ~0.4 were recorded in the temperature interval 350-400°C, where no cavitation was found.

Introduction

Aerospace industry has a great interest for the fabrication of complex parts from novel 7055 aluminum alloy, denoted as 7055 Al herein, due to its high strength combining with sufficiently high fracture toughness, fatigue, ductility and corrosion resistance [1]. These advantages make application of the 7055 Al efficient as a structural material for upper wing elements of airplanes. The fabrication of frames and thin-walled panels is required enhanced workability which can be achieved by making this material superplastic. It is known [2,3], that aluminum alloys having grain sizes less than ~10 μm are capable of achieving high superplastic ductility.

The utilization of superplastic forming technology in large bulk billets is currently limited because there exist difficulties in producing ultrafine grain structure [2]. Commercial 7055 Al produced by ingot metallurgy has an average grain size of ~100 μm [4]. A complex thermomechanical processing (TMP) was recently developed to achieve superplasticity in this material [4,5]. However, this technique has two important limitations. First, this TMP provides the formation of fine grained structure in sheets with a thickness less than 2 mm [4]. Second, a partially recrystallized structure consisting of grains with a large size of ~11 μm and recovered subgrains with a mean size of 2 μm resulted from this two-step TMP [4,5]. Volume fraction of recrystallized grains was about 64% [4,5]. Therefore, it is necessary to develop a new TMP producing a fully recrystallized structure and finer grains in the 7055Al.

It was shown [6-8], that equal channel angular extrusion (ECAE) is capable of producing a significant grain refinement in aluminum alloys due to occurrence of dynamic recrystallization during intense plastic straining in simple shear. Aluminum alloys subjected to ECAE with large strains could exhibit high superplastic properties [8-10]. Thus, the main aim of present study is to achieve superplasticity in the bulk billets of the 7055 Al using ECAE processing. Much interest has developed in imposing moderate strain to produce ultrafine grain structure in the 7055 Al, since it is extremely important on economic ground.

The present work is a continuation of studies in the 7055 Al, with the intent of evaluating its potential for superplasticity.

Material and Experimental Procedure

The 7055 Al with a chemical composition of Al-8.2%Zn-2.1%Mg-2.2%Cu-0.2%Zr (in weight %) was manufactured by direct chill casting and then homogenized at 470°C for 24 h and cooled in air. The alloy ingot was machined into rods with 20 mm diameter and 100 mm length. These rods were deformed to a true strain of 4 by ECAE at 300°C by repeated pressing without any rotation of the sample, i.e. route A [7,8]. An isothermal die with a circular internal cross-section and an L-shaped configuration with angles ϕ and ψ [6,8], both equal to 90°, was used for the extrusion. Deformation through this die produced a strain of about 1 on each passage [6-8]. Following the ECAE, tensile samples with 6 mm gauge length and 1.4×3 mm^2 cross-sections were machined from the extruded rods; the tensile axis was parallel to the former extrusion direction of the pressed rods. These samples were pulled to failure at temperatures ranging from 300°C to 450°C and strain rates ranging from 1.4×10^{-5} to 5.6×10^{-2} s^{-1}. Other details of mechanical tests were described in earlier reports [4,5].

Samples were analyzed by optical metallography and transmission electron microscopy (TEM) using procedures given in detail in previous works [4,5]. In the present study, samples pulled to failure were sectioned in planes containing the longitudinal (tension) and long transverse directions, and the microstructural evolution was examined under conditions of static annealing in grip sections and dynamic annealing in gauge sections at a strain rate of 1.4×10^{-3} s^{-1} in the temperature interval 300-450°C. Cavitation was measured in samples pulled to failure using the standard point-count technique. Samples for EBSD analysis, were mechanically polished and, finally, electropolished in the solution containing 10 ml of perchloric acid and 90 ml buthanol at 10°C. Misorientations of (sub)grain boundaries were determined by EBSD technique by means of hard and software of Oxford Instruments, Ltd installed on JSM-840 scanning electron microscope (SEM).

Experiments

Microstructure after ECAE. A typical TEM structure of the ECAE processed 7055 Al is shown in Fig.1a. It is clearly seen, the ECAE at 300°C to a strain of 4 results in the formation of fine crystallites with an average size of ~1 μm. Grain aspect ratio (AR), defined as the ratio of the grain dimension in the longitudinal (extrusion) direction to that in the transverse direction, is close to 1.3. High angle boundaries (HABs) with misorientations over 15 degree account for 82% of deformation-induced boundaries and, therefore, HABs highly dominate in the resulted structure (Fig.1b). Careful observation of many areas showed that microstructure of the ECAE processed 7055 Al was reasonably homogeneous, although in some areas, the recrystallized structure presented in Fig.2a alternates with regions of unrecrystallized and recovered subgrains. The volume fraction of recrystallized regions was over 85%. In the recrystallized regions, the grains outlined by HABs contained a few dislocations in their interiors ($\rho\sim10^{12}$ m^{-2}) but a part of them had moderate dislocation densities.

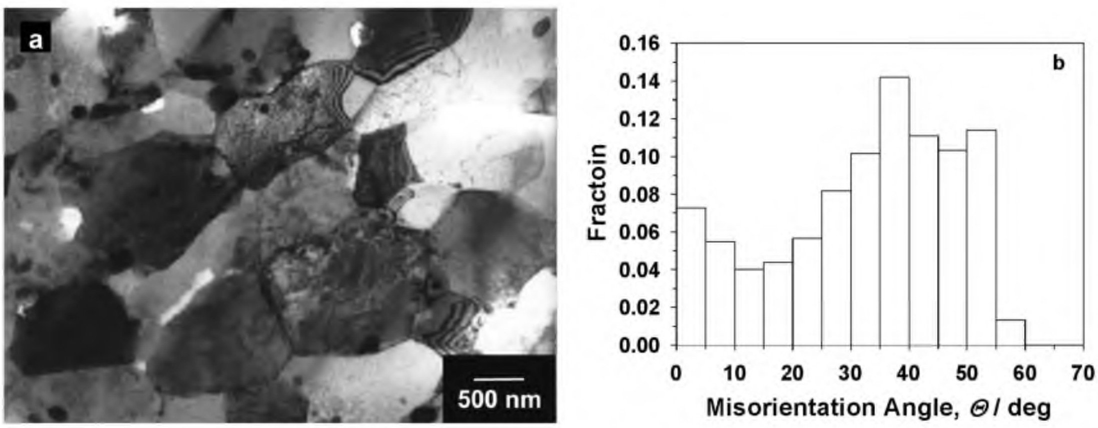

Figure 1. Initial microstructure of the 7055 Al alloy deformation to a strain of about 4 by ECAE processing at 300°C. (a) TEM micrograph and (b) misorientation diagram of (sub)grain boundaries

Superplastic Behavior. Typical true stress - true strain (σ–ε) curves for the 7055 Al with the ultrafine grained structure are presented in Fig.2a and 2b at two fixed temperatures of 300°C and 425°C, respectively, over a range of strain rates from 1.4×10^{-5} to 5.6×10^{-2} s^{-1}. Fig.2c represents the σ–ε curves at an initial strain rate of 1.4×10^{-3} s^{-1} and temperatures ranging from 300 to 450°C. It is seen that the flow stress is strongly dependent on strain that is untypical for superplastic deformation. There is a stress peak at a moderate strain. At low temperatures and/or high strain rates, a sharp softening after the stress peak can be attributed to extensive localized necking in gauge length (Fig. 3). Gradual strain softening after the peak stress tends to appear in higher strain with decreasing strain rate or increasing temperature. An apparent steady-state flow can be distinguished at T>400°C and $\dot{\varepsilon}\leq5.6\times10^{-4}$ s^{-1}, at which plastic flow in gauge lengths was found to be roughly uniform (Fig. 3) [2,3].

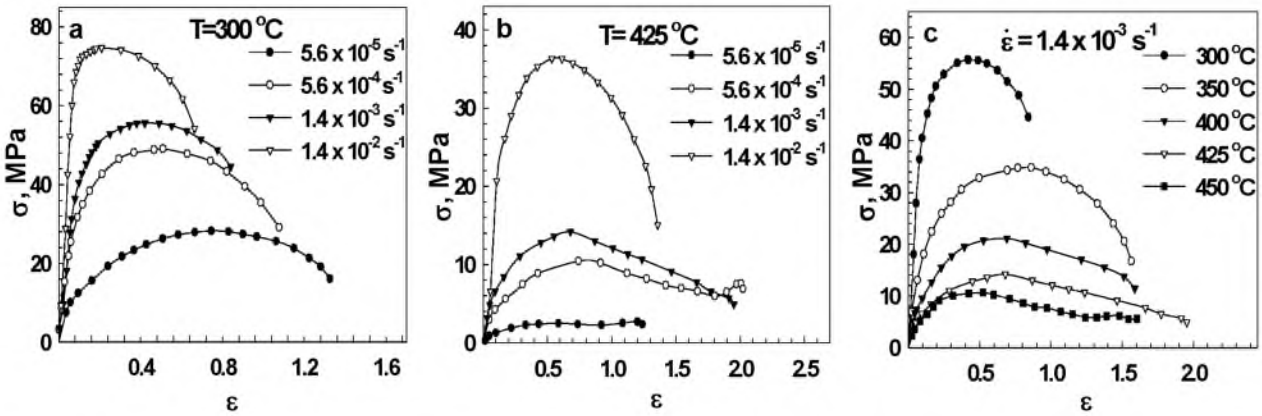

Figure 2. Typical true stress - true strain curves of 7055Al alloy subjected to ECAE. The strain rate dependence at (a) 300ºC, (b) 425ºC and (c) the temperature dependence at an initial strain rate of 1.4×10^{-3} s^{-1}.

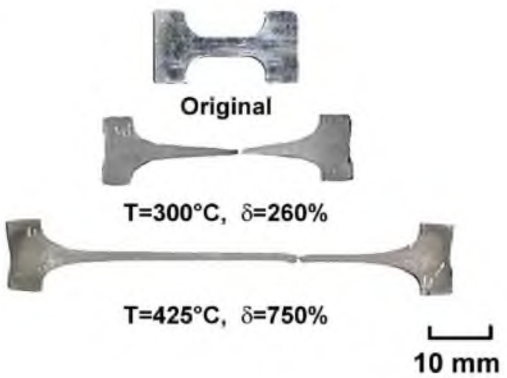

Figure 3. Untested sample and samples pulled to failure at $\dot{\varepsilon}=5.6\times10^{-4}$ s^{-1}.

Fig.4a gives a plot of the flow stress taken at ε~0.34 as a function of initial strain rate on a double logarithmic scale. It is apparent that at T≥350°C, the σ-$\dot{\varepsilon}$ curves exhibit a sigmoidal shape, as in standard superplastic alloys [2,3]. At 300°C, a highest elongation-to-failure, δ, of ~320% (Fig.4c) and a strain rate sensitivity, m~0.34 (Fig.4b) were found at $\dot{\varepsilon}=5.6\times10^{-5}$ s^{-1}. The m and δ values tend to increase with decreasing strain rate. Temperature increase leads to appearance of well-defined maximums of m and δ values in the strain rate range 10^{-4}– 10^{-2} s^{-1}, i.e. region 2 of superplasticity becomes distinctly distinguished [2,3]. Optimal strain rate for superplasticity, at which highest superplastic ductilities are observed, shifts to higher strain rates with increasing temperature from 300 to 450°C. At 425°C, the highest elongation-to-failure of 750% appears at a strain rate of 5.6×10^{-4} s^{-1} with m~0.46.

Temperature dependencies of the coefficient of strain rate sensitivity, m, and elongation-to-failure, δ, for the 7055 Al subjected to ECAE are shown in Fig.5. It is seen that the δ values of the

ECAE processed 7055 Al increases from 170% to 410% with temperature increase from 300 to 350°C whereas the m coefficient remains virtually unchanged (m~0.33). Higher temperatures result in increased the m value. Temperature dependence of the elongation-to-failure shows a maximum at 425°C. Then the δ value rapidly decreases.

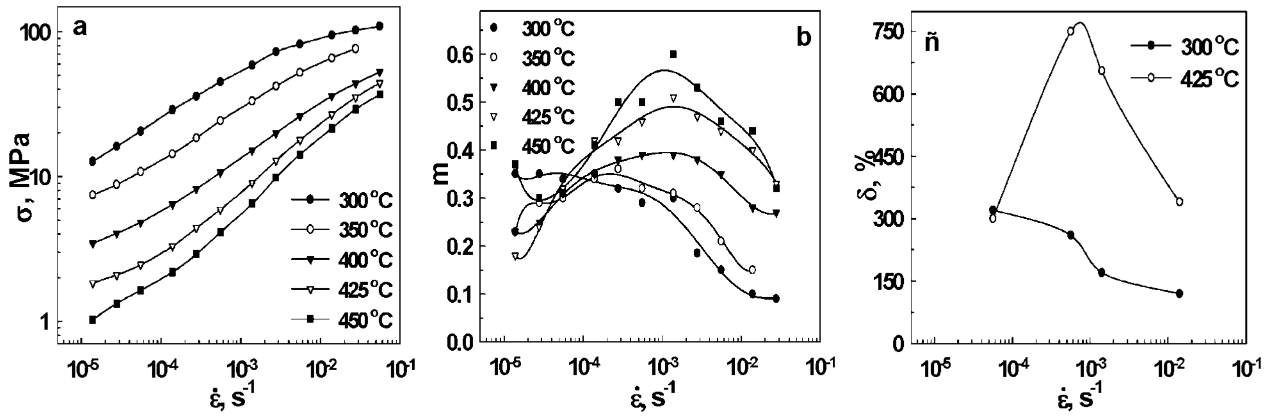

Figure 4. Strain rate dependence of flow stress, σ, taken at ε~0.34 (a), coefficient of strain rate sensitivity, *m,* taken at ε~0.34 (b) and elongation-to-failure (c).

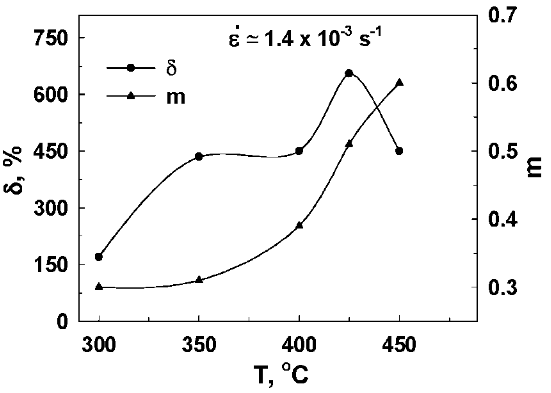

Figure 5. The coefficient of strain rate sensitivity, m, and elongation-to-failure, δ, as functions of temperature at $\dot{\varepsilon}\sim 1.4\times 10^{-3}$ s^{-1}.

Microstructural Evolution. Grain sizes developed after static annealing, L_s, dynamic annealing, L_d, and the grain aspect ratio in gauge sections are summarized in Table 1. Under static annealing the initial grains are essentially stable at T≤350°C and rapidly grow with increasing temperature at T≥400°C (Table 1). In general, non-uniformity of structure evolved during ECAE remains under static annealing.

No substantial grain growth takes place during superplastic deformation, and at 425°C, the superplastic deformation leads to an insignificant grain refinement (Fig.6a, Table 1) that can be associated with dynamic recrystallization. This is generally in contrast with structural changes in standard superplastic materials [2,3]. Superplastic deformation provides uniformity of microstructure (Fig.6a). The volume fraction of unrecrystallized structure decreases with increasing temperature in the range 300-400°C and at 425°C, the formation of highly uniform structure consisting of essentially equiaxed grains was revealed (Fig.6a). Notably grains remain reasonably equiaxed excluding T=350°C, at which the grain aspect ratio is high (Table 1).

At T≥400°C, etched cavities were revealed by optical microscopy technique (Fig.6a). Typical cross-sectional view is shown in Fig.6b. Average size of cavities, A, cavity aspect ratio, CAR, and volume fraction of porosity, V, as well are summarized in Table 2. In the temperature range 300-350°C the superplastic deformation induces only limited cavitations. With increasing temperature from 400°C to 450°C, the volume fraction of porosity and cavity size strongly increase approaching ~10% suggesting failure caused by cavity interlinkage [3]. The majority of large cavities was observed to grow along the tensile direction and to show an irregular and jagged shape (Fig.6b) suggesting plasticity-controlled cavity growth. Cavity interlinkage can result from the formation of cavity chains in the tension direction (Fig.6b).

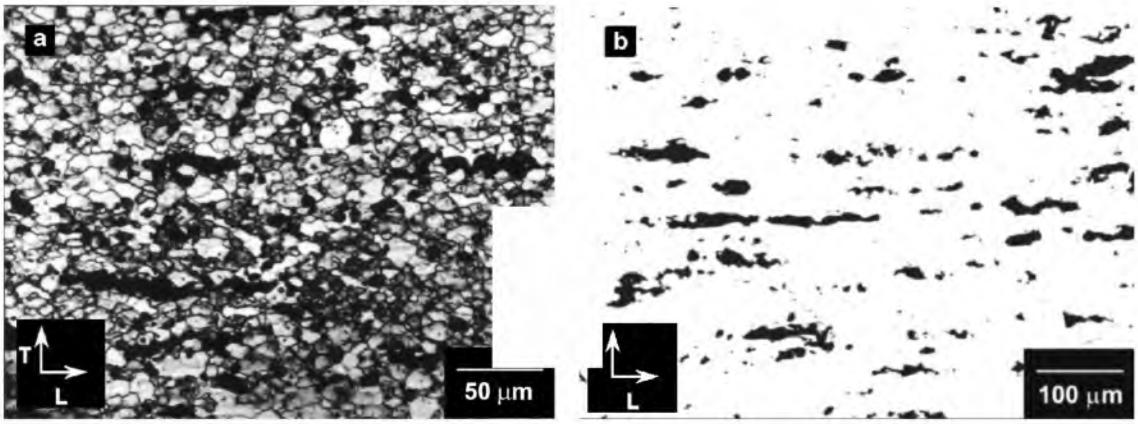

Figure 6. Microstructure evolved during deformation at T=425°C and $\dot{\varepsilon}\sim1.4\times10^{-3}$ s^{-1}

Thus, at T<400°C, the fracture occurs due to unstable plastic flow [3]. In the temperature interval 400-450°C, the pseudo-brittle fracture associated with nucleation, growth and interlinkage of internal voids takes place [3].

Table 1. Average grain size, L_s and L_d, after static annealing and superplastic deformation and aspect ratio of grains in gauge section for the samples strained up to failure at a strain rate of 1.4×10^{-3} s^{-1} and different temperatures.

T, [°C]	300	350	400	425	450
Local strain in gauge section (the equivalent time of static annealing in grip section, h)	ε=0.9 (0.87)	ε=1.7 (1.40)	ε=1.8 (1.43)	ε=2.0 (1.83)	ε=1.8 (1.43)
L_s [μm]	1.4	2.2	5.4	11.4	15.0
L_d [μm]*	2.0/1.5	2.5/1.6	9.8/8.0	10.9/8.6	15.8/12.0
Aspect ratio	1.30	1.56	1.23	1.26	1.32

*Numerator and denominator are grain sizes measured in the longitudinal and transverse directions,

Table 2. Average cavity size, A, coefficient of cavity aspect ratio, CAR, and porosity volume fraction, V for the 7055 Al strained at $\dot{\varepsilon}=1.4\times10^{-3}$ s^{-1} up to failure under various temperatures.

T, [°C]	350	400	425	450
A [μm]*	-	10/8.1	14.4/9.5	17.8/11.1
CAR	-	1.2	1.5	1.6
V, %	-	5.1	8.7	8.6

*Numerator and denominator represent cavity sizes measured in the longitudinal and transverse directions, respectively.

Discussion

The present study demonstrates the feasibility of achieving grain refinement and superplastic ductilities in the commercial 7055 aluminum alloy in as-cast condition. This work established ECAE as a very effective processing technique to introduce ultrafine grain size of ~1 μm in bulk billets of the 7055 Al thereby imposing a moderate true strain of 4 at 300°C. The 7055 alloy behaves during ECAE processing as a dilute aluminum alloy in which ultrafine grain structure is developed after a true strain of about 4 [6,7]. The presence of incoherent Al_3Zr dispersoids does not lead to the shift of the formation of recrystallized structure to large strain as that in Al-Mg-Sc alloys containing coherent Al_3Sc dispersoids [9,11]. However, the low fraction of Al_3Zr dispersoids could not impede grain boundary mobility and effectively restrict growth of the ultrafine grains at T≤350°C. As a result, the ECAE processed 7055 Al exhibits highest elongation-to-failure of 750% in recrystallized condition with relatively large grain size of ~10 μm at a temperature of 425°C, at which an extensive static growth of fine grains takes place. At lower temperatures, the 7055 Al demonstrates moderate superplastic properties.

Conclusions

1. A cast 7055 alloy with an initial grain size of ~100 μm was subjected to ECAE processing at a temperature of 300°C to a strain of ~4, thereby reducing the grain size to ~1 μm. Ultrafine (≤2 μm) and fine (≤10 μm) grain sizes were retained at temperatures as high as 350°C and 425°C, respectively.
2. Moderate tensile elongations of ≤435% were recorded in the ECAE processed 7055 Al in the temperature range 300-400°C. A maximum of elongation-to-failure of 750% was found at a temperature of 425°C and an initial strain rate of 5.6×10^{-4} s^{-1} with corresponding the strain rate sensitivity coefficient of about 0.46.

Acknowledgement

The financial support by the International Science and Technology Center under Project no. 2011 and Light Metal Education Foundation are gratefully acknowledged

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