Transgranular Deformation Controlled Superplasticity in Aluminum-based Solid Solution

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Abstract

High temperature tensile deformation behavior for an Al-Cu solid solution alloy consisting of either coarse grains or columnar grains has been investigated with a special reference to the occurrence of Class I superplasticity. Enhanced ductility over 400% is observed under an optimum condition of strain rate and temperature. The superplastic-like behavior should be attributed to a moderately strain rate sensitive deformation process which is governed by the solute drag motion of dislocations.

1. Introduction

It is well known that the superplasticity (fine structure superplasticity [1]) of the grain boundary sliding control appears in the alloy consisting of the microstructure that is thermally stable and initial grain size 10μm or smaller. Though as a microstructure refinement method, there are thermomechanical treatment (TMT) [1], powder metallurgy (PM) [2], mechanical alloying (MA) [2], rapid solidification (RS) [3] and so on, the manufacturing cost of the plate is also 3 to 30 times as high as usual rolling sheet [4].

Metallic materials consisting of submicron sized ultra-fine grains often exhibit high strain rate superplasticity [1], in addition to an excellent strength and toughness combination at room temperature and to low temperature superplasticity [5]. Though the microstructure refinement processes such as equal channel angular pressing (ECAP) [6], high pressure torsion (HPT) [7], accumulative roll bonding (ARB) [8], cyclic extrusion compression (CEC) [9] and bulk mechanical alloying (BMA) [10] have been examined, there are many problems to be solved as for manufacturing cost and manufacturing process of bulk materials prior to the practical application.

According to previous reports, on the other hand, pseudo-superplastic behavior is observed in solid solution alloys having medium to coarse grain size, the creep stress exponent of which is close to three. The information about this type of superplasticity seems to be quite useful. From such a point of view, the high temperature deformation behavior has widely been studied on solid solution alloys based on aluminum[11], magnesium[12], titanium[13], copper[13], zinc[14] and iron[15].

The enhanced ductility of these alloys is thought to be brought about by their comparatively large strain rate sensitivity, which originates from the solute drag of glide dislocations [16]. According to Weertman [17,18], the stress exponent of the solute drag creep is 3, and the strain rate is given as follows:

$$\dot{\varepsilon} = A\left(\frac{EbD_{\mathrm{sol}}}{kT}\right)\left(\frac{\sigma}{E}\right)^{3} \quad (1)$$

Here A is a dimensionless material constant, D_{sol} is the interdiffusion coefficient, E is Young's modulus, b is the magnitude of Burgers vector, k is Boltzmann constant, and T is the absolute temperature.

From eqn. (1), the grain size (d) does not influence the strain rate of the solute drag creep. According to the classification of Sherby and Burke [19], the stress exponent of Class I alloys is 3 to 3.5, while that of Class II alloys is 5 to 7. Nieh et al. [20] named the enhanced ductility observed in Class I solid solutions as "Class I superplasticity". In general there exists a positive relation between ductility and stress exponent[24]. So the ductility of coarse grained Class I solid solution(n=3) tends to be lower than that for fine grained material (n=2). However, extremely large elongation is not always required, as in the case of sheet forming in which the uniform elongation up to around 200% is sufficient. Class I alloys have merit that no special heat treatment for grain refining is needed during fabrication process.

The purpose of this study is to investigate the high temperature ductility of Al-2mol%Cu solid solution alloy having either columnar grains or equiaxed coarse grains.

2. Experimental Procedure

An Al-Cu alloy consisting of coarse grains and columnar grains was used in this work. Its chemical composition is shown in Table 1. The coarse-grained specimens were prepared by a sequential process of homogenization treatment of cast billet, hot rolling, middle annealing and cold rolling. On the other hand, the columnar-grained bars of 6mm diameter were directly obtained by the Ohno continuous casting (OCC) method. Tensile test specimens having two types of gauge sections were cut out of these starting materials: 12mm long, 5mm wide and 2mm thick for the coarse-grained sheet specimens, and 12mm long and 5mm in diameter for the columnar-grained cylindrical specimens. They were then solution treated at 833K for 7.2ks. Just before the tensile test, the gauge sections of the specimens were electrolytically polished for microstructural observation.

Typical microstructure of each material before tensile test is shown in Figure 1 (coarse grains) and Figure 2 (columnar grains). Microstructure of the coarse-grained samples consists of equiaxed grains having a size as large as 0.98mm. On the other hand, mean length and width of columnar grains are 0.88mm and 17.5mm, respectively. In addition, their longer axes are oriented nearly parallel to the tensile axis, suggesting that grain boundary sliding will be very difficult because little or no shear stress is exerted along grain boundaries.

An Instron type universal testing machine was used for high temperature tensile test. Tests were conducted in air at temperatures between 773 to 833K and strain rates between 3×10^{-5} and $10^{-2}s^{-1}$. The equilibrium phase diagram of Al-Cu [21] shows that only *α* phase is stable between 803 and 833K, while at 773K the alloy consists of both *α* phase and *θ* phase ($CuAl_2$), the volume fraction of the latter being about 2vol% [21].

Table 1: Chemical compositions of Al-Cu alloy studied.

Element	Cu	Si	Fe	Mg	Al
Content (mol%)	2.00	0.002	0.001	0.000	Bal.

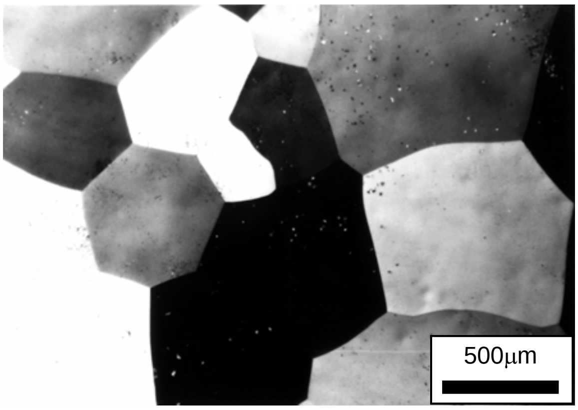

Figure 1: Initial microstructure of coarse-grained Al-2mol%Cu alloy.

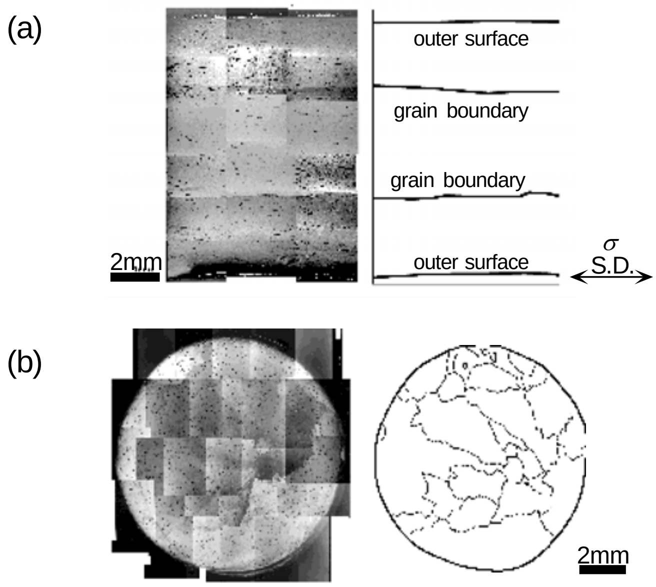

Figure 2: Initial microstructure of columnar-grained Al-2mol%Cu alloy. (a) longitudinal section, (b) cross section.

3. Results

3.1 Elongation

Figures 3-(a) and 3(b) show elongation to fracture as a function of initial strain rate for the coarse- grained and columnar-grained specimens, respectively. The elongation of both materials tends to increase in low strain rate range at 773K, at which the volume fraction of *θ* phase is about 2vol%. The elongation exceeds 200% at a strain rate lower than $3\times10^{-4}s^{-1}$ of coarse-grained specimens and $3\times10^{-3}s^{-1}$ of columnar-grained ones. This means that small amount of second phase has no remarkable effects on the ductility.

Above 803K, i.e., in the single-phase range, the alloy shows an enhanced ductility over 200% in a relatively wide strain rate range.

The largest elongation observed in the coarse-grained specimen is 262% at 833K and $1x10^{-2}s^{-1}$and that in coarse-grained specimen is 471% at 803K and $1x10^{-4}s^{-1}$. Thus the enhanced ductility is obtained in both coarse-grained and columnar-grained specimens. It is also to be noted that high strain rate superplasticity is observed at and above strain rates above $10^{-2}s^{-1}$. The elongation of the columnar-grained specimens is much larger than that of coarse-grained specimens.

3.2 Stress exponent

Figures 4-(a) and 4(b) show, respectively, log-log plots of initial strain rate versus modulus normalized tensile strength for the coarse-grained and columnar-grained specimens. In normalizing tensile strength, the Young's modulus of pure aluminum was used [22]. The stress exponent is about 3 for both specimens in wide strain rate and temperature range, meaning that Al-2mol%Cu falls under Class I alloy.

On the other hand, stress exponents of both specimens tend to increase up to about 5 in higher strain rate and lower temperature range. Such a transition to the creep behavior of Class II alloy is probably ascribed to the break away of glide dislocations from solute atmosphere.

The high ductility observed in this alloy seems to originate from the creep characteristics of Class I solid solution, because the strain rate range in which the stress exponent is close to 3 coincides with that for the occurrence of high ductility. It is to be noted from the results obtained at 773K that the alloy shows superplastic-like behavior, even if a small amount of second phase particles are present in the matrix.

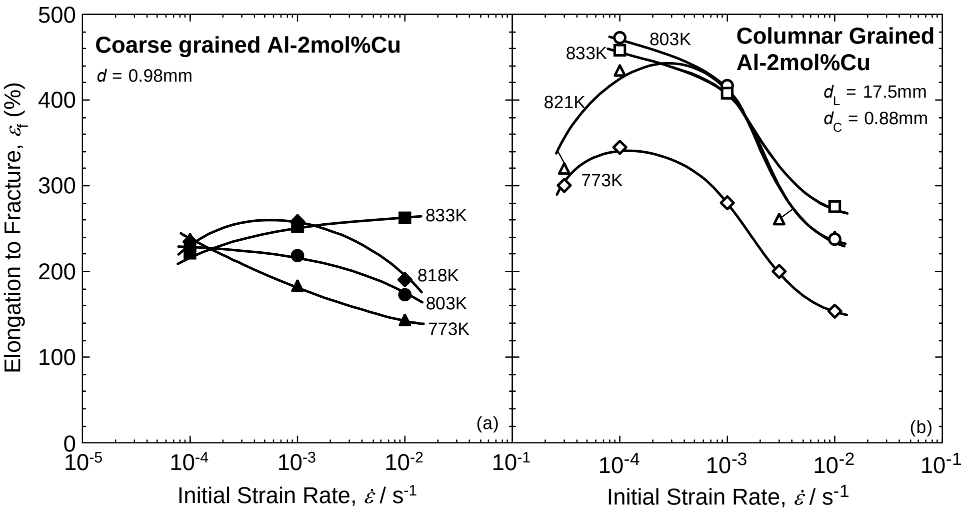

Figure 3: Elongation to fracture as a function of initial strain rate.
(a)coarse-grained specimens, (b)columnar-grained specimens.

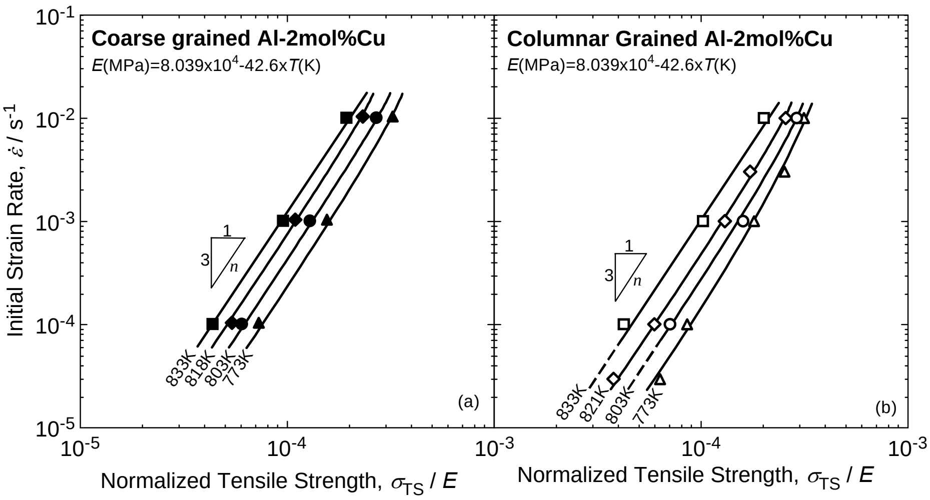

Figure 4: Initial strain rate as a function of modulus normalized tensile strength.
(a)coarse-grained specimens, (b)columnar-grained specimens.

3.3 Activation Energy for Deformation

Figure 5 shows Arrehenius plots of log strain rate versus reciprocal absolute temperature at a constant modulus-normalized tensile strength of 1x10^{-4}. The activation energy for deformation is, respectively, 120kJ/mol and 125kJ/mol for the coarse-grained and columnar-grained specimens, both being close to the activation energy for the interdiffusion of solute copper atoms in aluminum matrix[23].

From these results, the high ductility observed in this study can be regarded as a kind of superplasticy, the strain rate of which is governed not by the grain boundary sliding but by the solute drag creep.

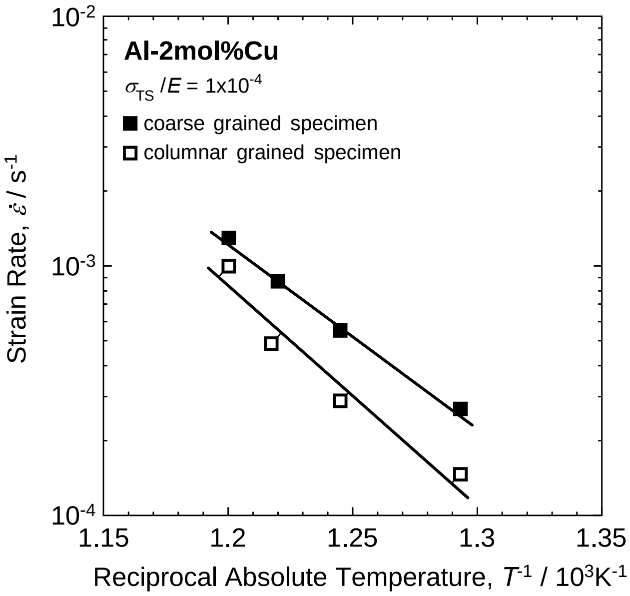

Figure 5: Log strain rate vs. reciprocal absolute temperature at σ_{TS}/E =1x10^{-4}.

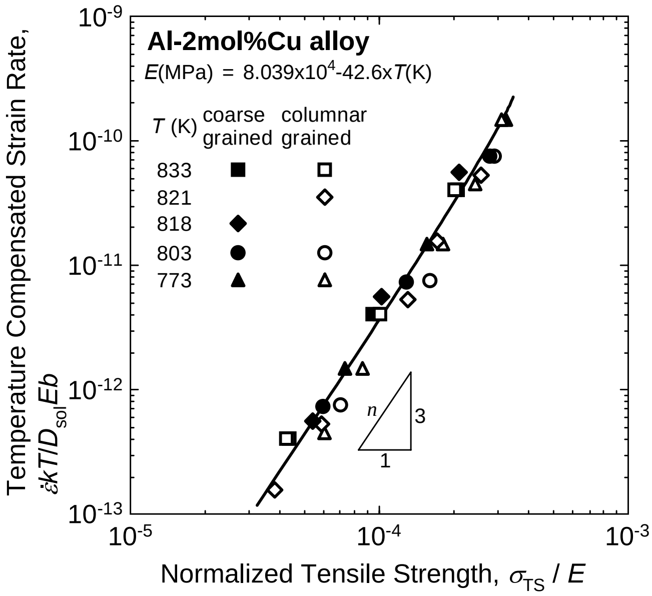

Figure 6: Log-log plots of $\dot{\varepsilon}kT/D_{sol}Eb$ vs. σ_{TS}/E.

4. Discussion

The ultra-high ductility observed in this alloy is regarded as a result of superplastic deformation which is controlled by the solute drag motion of dislocations. Equation (1) will then be rewritten as follows:

$$\frac{\dot{\varepsilon}kT}{D_{sol}Eb} = A\left(\frac{\sigma}{E}\right)^3 \quad (2)$$

According to Eqn.(2), log-log plots of normalized tensile strength versus temperature compensated strain rate should fall on a single straight line with a slope of 3. Figure 6 shows the result of plotting. As expected, the stress exponent is about 3 below normalized stresses of 2.2x10^{-4}, while it starts to increase up to about 5 above 2.2x10^{-4}.

We separately tried to plot normalized tensile strength against elongation to fracture for both types of Al-2mol%Cu alloy specimens. It was found that the ductility exceeds 200% in the solute-drag creep region, but decreases rapidly in the power-law breakdown creep region.

5. Conclusions

(1) Al-2mol%Cu solid solution alloy exhibits an excellent hot ductility over 200% either in the columnar-grained or in the coarse-grained specimens.
(2) The observed values of stress exponent and activation energy for deformation, together with the fact that the contribution of grain boundary sliding is relatively small, strongly suggest that the high ductility is caused by superplastic deformation which is controlled by the solute-drag creep.

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