Superplastic Deformation Mechanisms in Powder Metallurgically Processed Al-5Mg-2.2Mn Alloy

Kenji Higashi^{☆1}, Yasushi Matsumura^{☆1}
Mamoru Mabuchi^{☆2} and Shinji Tanimura^{☆1}

^{☆1} College of Engin, Dept. Mech. Sys. Engin, Uni, of Osaka Prefecture, Sakai 593.

^{☆2} National Industrial Research Institute of Nagoya, 1-1 Hirate-cho Kita-ku, Nagoya 462.

Received June 14, 1994

The tensile behavior of a powder metallurgically processed Al-5mass%Mg-2.2mass%Mn alloy with a fully recrystallized fine grained structure of 3 μm in size was characterized at strain rates between 10^{-4} and 2 s^{-1} at temperatures from 748 to 823 K. This alloy exhibited superplasticity at high strain rates around 10^{-2} s^{-1} . A maximum elongation of 570 % was obtained at a constant strain rate of $6 \times 10^{-3} \text{ s}^{-1}$ at 823 K. An analysis of the threshold stress indicated that the true stress exponent is 2 for all testing temperatures and the true activation energy for superplastic flow is equal to that for lattice diffusion in aluminum. It is postulated that superplastic flow in the P/M Al-Mg-Mn alloy is controlled by a grain boundary sliding mechanism accommodated by dislocation climb or glide controlled by lattice diffusion.

1 Introduction

It was recently reported that very fine grained aluminum alloys were obtained by a combination of powder metallurgy and/or advanced processing methods, including mechanical alloying¹⁻⁶⁾, consolidation from amorphous powders⁷⁻⁹⁾ or nanocrystalline powders¹⁰⁾ and physical vapor deposition¹¹⁾. A group of the powder metallurgically processed Al-Cu, Al-Mg and Al-Zn-Mg system alloys with a large amount of Cr, Mn or Zr has been made to a fine grained super-plastic structure of less than 5 μm by optimum powder metallurgical processings. These P/M alloys showed large elongations of more than 500 % at high strain rates over about 10^{-2} s^{-1} and consist of two groups, statically recrystallized and

dynamically recrystallized alloys due to the difference of recrystallization behavior^{12,13)}. The former are P/M aluminum alloys with Cr or Mn, and the latter are other P/M aluminum alloys including Zr.

In this paper, the deformation mechanisms of high strain rate superplasticity in a P/M Al-5mass%Mg-2.2mass%Mn alloy with a fully recrystallized fine grained structure of about 3 μm are addressed from the experimental data characterized at various strain rates and temperatures.

2 Experimental procedures

The chemical compositions of powder metallurgically processed aluminum alloys used in the present work are given as

Al-5mass%Mg-2.2mass%Mn. A P/M aluminum alloy was produced in the form of extruded bars by Technical Research Laboratories of Sumitomo Light Metal Industries Ltd. then processed by superplastic thermo-mechanical treatment into thin rolled sheet form at our laboratory. Tensile samples with 5 mm gauge length and 4 mm width were machined from these rolled sheets, which gauge length was parallel to the rolling direction. Tensile tests were carried out in air at temperatures between 748 and 823 K and in a wide strain rate range from 10^{-4} and 2 s^{-1} on the tensile testing machines controlled by computers that allowed the true constant strain rate tests. The flow stresses for each sample at given strain rates and temperatures were determined from the fixed true strain of 0.1.

3 Results and analysis

The elongation of the P/M Al-Mg-Mn alloy at testing temperatures between 748 and 823 K is shown in the bottom part of Fig. 1 as a function of strain rate. An optimum superplastic strain rate range for large elongations more than 300 % at each temperature is nearly 10^{-2} s^{-1} , and the maximum elongation values seem to increase with increasing temperature. A maximum elongation of 570 % was obtained at a relatively high strain rate of $6 \times 10^{-3} \text{ s}^{-1}$ at 823 K.

The flow stress of the P/M Al-Mg-Mn alloy at various temperatures as a function of strain rate is shown in the top part of Fig. 1. The flow stress increased with increasing strain rate, there are typical curves of sigmoid have been observed for superplastic materials. In the low strain rate regime, the low strain rate sensitivity indicates an apparent threshold stress. In the P/M Al-Mg-Mn alloy with a large amount of Mn, additional mechanisms may be responsible for inclusion of oxides from

the aluminum alloys powders and a large amount of fine particles of Al_6Mn by the powder metallurgical process providing resistance to grain boundary sliding or acting as effective barriers to dislocation motion. In the high strain rate range where superplasticity was obtained, a high strain rate sensitivity of about 0.5 ($n=2$) was obtained, with corresponding relatively large elongations.

Superplastic deformation is usually described by an equation for power-law creep of the form¹⁴⁾,

$$\frac{\dot{\epsilon} k T}{D G b} = A \left(\frac{b}{d} \right)^p \left(\frac{\sigma}{G} \right)^n \quad (1)$$

where A is a geometrical constant; $\dot{\epsilon}$ the strain rate; σ the stress; n ($1/m$) the stress exponent; k Boltzmann's constant; T the absolute temperature; d the grain size; b the Burgers vector; p the grain size exponent; G the temperature-dependent shear modulus and $D = D_0 \exp(-Q/RT)$ the appropriate diffusivity (R the gas constant; D_0 the frequency factor

Fig. 1 Elongation and stress of the P/M Al-Mg-Mn alloy at temperatures between 748 and 823 K as a function of strain rate.

and Q the activation energy of an appropriate diffusion process). In the case where a threshold stress σ_0 is indicated, σ is usually replaced by $(\sigma - \sigma_0)$. An apparent temperature-dependent threshold stress can be estimated from the only mechanical data from the superplastic strain rate regime of the top part of Fig. 1 using the approach suggested by Mohamed¹⁵⁾. Fig. 2 shows a double linear plot of σ against $\dot{\epsilon}^m$ for a value $m=0.5$ predicted by the most theoretical model of superplastic deformation. Numeric processing enabled to determine σ_0 values for each testing temperature resulting in the best linear fit of the σ vs. $\dot{\epsilon}^m$ dependence. The values 5.15, 3.65, 2.72 and 1.60 MPa for the threshold stress in the case of $m=0.5$ were obtained at temperatures of 748, 773, 798 and 823 K respectively.

The mean value of the grain size d annealed for 1.8 ks at each testing temperature is shown in Table 1, indicating that grain size d increases slightly from 2.3 to 3 μm with increasing temperature. Including in Table 1 the threshold stress measured in Fig. 2, and the shear modulus is obtained from dynamic modulus studies on the 5056 (Al-Mg-Mn) alloy¹⁶⁾. From the values in grain size, thresh-

Fig. 2 A double linear plot of σ against $\dot{\epsilon}^m$ for a value $m=0.5$ predicted by the most theoretical model of superplastic deformation.

Table 1
The values of grain size, threshold stress and shear modulus.

Temperature (K)	748	773	798	823
Grain size (μm)	2.30	2.51	2.67	3.00
Threshold stress (MPa)	5.15	3.65	2.72	1.60
Shear modulus (GPa)	14.20	12.57	10.71	8.61

old stress and shear modulus shown in Table 1, the $\log((\sigma - \sigma_0)/G)$ vs. $\log(\dot{\epsilon}d^2)$ dependence could be obtained in a double logarithmic scale, using the value of 2 in grain size exponent p which was reported for the superplastic Al-5Mg-0.5Mn aluminum alloy¹⁷⁾. From the relationship between $\log((\sigma - \sigma_0)/G)$ and $\log(\dot{\epsilon}d^2)$ the true activation energy Q can be evaluated according to eqn.(1). The measured activation energy Q was 142 kJ/mol, which was the value of the reported activation energy for lattice diffusion in pure aluminum (142 kJ/mol¹⁸⁾).

Thus, it is possible to normalize the

Fig. 3 Diffusion- and grain-size-compensated strain rate vs. modulus-compensated effective stress for the fine grained P/M Al-5Mg-2.2Mn alloy.

superplastic mechanical data in Fig. 1 by plotting them in the form of eqn.(1). By using the lattice diffusion coefficient D_L and the normalized effective stress $\{(\sigma - \sigma_0)/G\}$, the summary is obtained for testing temperatures as shown in Fig. 3. The geometrical constant value A of the constants 5×10^5 is estimated in the form of eqn.(1), the constitutive equation of the superplastic deformation for the P/M Al-Mg-Mn alloy is given by

$$\frac{\dot{\epsilon} k T}{D_L G b} = 5.0 \times 10^5 \left(\frac{b}{d} \right)^2 \left(\frac{\sigma - \sigma_0}{G} \right)^2 \quad (2)$$

The result is in very close agreement with the conclusion that superplastic flow in the fine grained P/M Al-Mg-Mn alloy is controlled by a grain boundary sliding mechanism accommodated by dislocation climb or glide controlled by lattice diffusion.

4 Summary

High strain rate superplasticity was obtained in the powder metallurgically processed Al-5mass%Mg-2.2mass%Mn aluminum alloy. Introducing a threshold stress, shear modulus and grain size into the rate equation, the true values of n and Q established as 2 and 142 kJ/mol respectively. It is postulated that superplastic flow in this alloy is controlled by a grain boundary sliding mechanism accommodated by dislocation climb or glide controlled by lattice diffusion.

5 References

- 1) T.G.Nieh, P.S.Gilman and J.Wadsworth, *Scripta. Metall.*, **19** (1985)1375.
- 2) T.R.Bieler, T.G.Nieh, J.Wadsworth and A.K.Mukherjee, *ibid.*, **22** (1988)81.
- 3) K.Higashi, T.Okada, T.Mukai and S.Tanimura, *ibid.*, **25** (1991)2053.
- 4) K.Higashi, T.Okada, T.Mukai, S.Tanimura, T.G.Nieh and J.Wadsworth, *ibid.*, **26** (1992)185.
- 5) K.Higashi, T.Okada, T.Mukai and S.Tanimura, *ibid.*, **26** (1992)761.
- 6) K.Higashi, T.Okada, T.Mukai and S.Tanimura, *Mater. Sci. Eng.*, **A159** (1992)L1.
- 7) A.Inoue, K.Kita, K.Ohtera, H.Kimura and T.Masumoto, *J.Mater.Sci.Lett.*, **7** (1988)1287.
- 8) K.Ohtera, A.Inoue and T.Masumoto, *Mater. Sci. Eng.*, **A134** (1991)1212.
- 9) K.Higashi, T.Mukai, S.Tanimura, A.Inoue, T.Masumoto, K.Kita, K.Ohtera and J.Nagahora, *Scripta Metall. Mater.*, **26** (1992)191.
- 10) H.Nagahama, K.Ohtera, K.Higashi, A.Inoue and T.Masumoto, *Philos. Mag. Lett.*, **67** (1993)225.
- 11) R.W.Gardiner and M.C.McConnell, *Metals and Materials*, **3** (1987)254.
- 12) K.Higashi, S.Tanimura and T.Ito, *MRS Sym. Proc. Vol.196*, Pittsburgh, (1990)385.
- 13) K.Higashi, S.Itsumi, M.Hoshikawa, Y.Matsumura, T.Ito, S.Tanimura and H.Yoshida, *Superplasticity in Advanced Materials*, The Jap. Society for Research on Superplasticity, Osaka, (1991)575.
- 14) J.E.Bird, A.K.Mukherjee and J.F.Dorn, "Quantitative Relation Between Properties and Microstructure", ed by D.G.Brandon and A.Rosen, Israel Universities Press, (1969)255.
- 15) F.A.Mohamed, *J. Mat. Sci.*, **18** (1983)582.
- 16) Y.Takeuchi, S.Komori, N.Noda and H.Nyuko, *J. Thermal Stresses*, **2** (1979)233.
- 17) H.Iwasaki, S.Hayami, K.Higashi and S.Tanimura, *Mater. Sci. Forum*, **94-96** (1992)759.
- 18) H.J.Frost and M.F.Ashby, "Deformation Mechanism Maps", Pergamon, Oxford, (1982).