THE DEFORMATION BEHAVIORS OF Al_2O_3 PARTICLE REINFORCED ALUMINUM COMPOSITES

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ABSTRACT   The deformation behaviors of aluminum composites with 1-30vol% Al_2O_3 particle prepared by the air-atomized powder (PM materials) and the mechanically alloyed powder (MA materials) have been investigated at various temperatures. The yield stress and the elastic modulus of the both materials are linearly increased with increasing the Al_2O_3 particle content, however, the modulus is very close to the lower bound predicted by the rule of mixture. So it can be considered that the contribution of the strength of the particles to the strengthening of the composite is significantly low. The dominant factor of strengthening of the composite can be considered as the high dislocation area (work hardening region) in the vicinity of hard particles due to the difference in thermal expansion between the Al_2O_3 particle and the aluminum matrix. The stress exponents are 22.5 in PM and 22 in MA materials. The apparent activation energies of PM and MA materials are 236 and 223kJ/mol, respectively.

Keywords: *Aluminum Composite, Powder metallurgy, Mechanical alloying, Alumina particle*

INTRODUCTION

　　　Ceramic particle reinforced aluminum matrix composites such as SAP alloy [1] will be expected to enhance the high temperature strength. Especially, in the composites produced by powder metallurgy such as rapidly solidification and mechanical alloying techniques, the refinement of grain size and the homogeneous dispersion of particles can be easily accomplished and the composites exhibit higher Young's modules and yield strength [2,3]. The strengthening mechanisms of particle dispersion materials have been explained as the interaction between dislocations and particles by Orowan [4,5] or Srolovitz [6,7] models. But Nardone et al [8] has been reported that the calculated Orowan stress of SiC particle reinforced aluminum composites is far lower than the observed strength. They have been suggested that the yield stress is considerably influenced by the distribution of particle size, the shape and the interparticle spacing in a real materials. On the other hand, at elevated temperature particle reinforced composites show high stress exponent value (n value; n>20), and the activation energy is very high compared with the self diffusion of common aluminum alloys [2,9,10].

　　　The purpose of this study is to investigate the strengthening mechanisms and the high temperature deformation properties of Al_2O_3 particle reinforced aluminum composites produced by powder metallurgy.

EXPERIMENTAL PROCEDURE

Table 1 Microstructures of PM and MA materials.

Materials	Relative density, $\rho / \%$	Grain size, dg / nm	Particle size, $dp / \mu m$	Fe / mass%
PM Al-1vol%Al_2O_3	98.8	198	0.29 ± 0.15	---
5vol%Al_2O_3	97.9	291	0.33 ± 0.14	---
10vol%Al_2O_3	97.4	350	0.29 ± 0.12	---
20vol%Al_2O_3	94.6	---	0.31 ± 0.12	---
30vol%Al_2O_3	97.1	193	0.32 ± 0.16	---
MA Al-1vol%Al_2O_3	99.9	153	0.11 ± 0.13	0.21
3vol%Al_2O_3	99.7	---	0.13 ± 0.15	---
5vol%Al_2O_3	100.5	138	0.10 ± 0.21	0.50
10vol%Al_2O_3	99.3	146	0.15 ± 0.16	0.74

The elemental materials were pure aluminum powders (purity: 99.9mass%, powder size: <45μm) produced by air-atomizing and Al_2O_3 particles (purity: 99.99mass%, average particle size: 0.45μm). The volume fractions of Al_2O_3 particles were in the range from 1 to 30vol%. The composites were made from air-atomized (PM materials) and mechanically alloyed powders (MA materials) that were milled in argon atmosphere for 64.8ks using a vibration ball mill. The powders prepared by both techniques were cold pressed to form compacts, and then the compacts were extruded at 873K after degassing in vacuum at 673K for 7.2ks.

Specimens for the compression and tensile tests were annealed at 773K for 1.8ks, and then air-cooled before the tests. The gauge sizes of specimens were ϕ6mm $\times$ 10mm for compression and ϕ3.5mm $\times$ 20mm for tensile test. Compression and tensile tests were carried out in air in the temperature range of RT-773K, and the initial strain rate was $4.6 \times 10^{-4}s^{-1}$ in both tests.

RESULT AND DISCUSSION

A. Microstructure of composites

The characteristics of the Al_2O_3 particle reinforced aluminum composites, PM and MA materials, are shown in **Table 1**. The relative densities of MA materials are higher than that of PM materials, because MA materials contain Fe (Table 1) which is provided from a mill pot and balls during mechanical alloying process [11], therefore, the apparent relative density of MA materials increases. The sizes of the Al_2O_3 particles are about 0.3μm in PM materials and 0.10-0.15μm in MA materials, and the grain size of the composites determined by Scherrer's equation are 200-300nm in PM materials and 130-150nm in MA materials. The decrease in the size of Al_2O_3 particles and grains of MA materials are due to the milling treatment. The mean interparticle spacing, λs, is shown in Fig.1
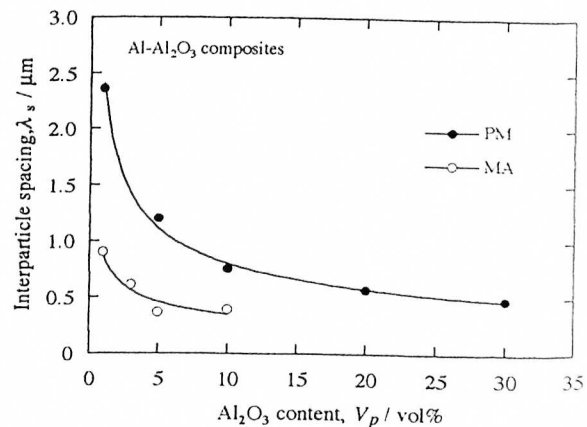

Fig.1 Relationship between the volume fraction of Al_2O_3 particle and the interparticle spacing.

The interparticle spacing is calculated by a following equation [12];

$$\lambda_s = \left(\frac{2}{3}\right)^{\frac{1}{2}} \times d_p \times V_p \quad (1)$$

where d_p is a particle size and V_p is the volume fraction of the particles (Table 1). In Fig.1, the λs decreases with the Al_2O_3 particle content in both materials, and the λs of MA materials is smaller than that of the PM materials due to the refinement of Al_2O_3 particle by the milling.

In the dispersion-strengthening composite materials, the fine second phases or ceramic particles impede the motion of dislocation, and the dispersion strengthening by Orowan model can be expressed as the following equation [13,14];

$$\tau_{or} = \frac{G_m b}{\lambda_s} \quad (2)$$

where G_m is the shear modulus (27GPa) and b is the Burger's vector of the matrix (0.286nm). It can be easily imagined from Eq.2 that the strengthening by the particles becomes effective when the interparticle spacing is less than 0.3 μm [12]. The interparticle spacing shown in Fig.1 is greater than 0.3μm, so it can be considered that the particles do not act as effective obstacles for the motion of dislocations in the composites.

B. Deformation behavior and strengthening mechanisms

The 0.2% proof stress, $\sigma_{0.2}$, and the fracture elongation, ε_f of the PM and MA materials in tensile tests at room temperature are shown in **Fig.2**. It is noted that $\sigma_{0.2}$ is linearly increased with the volume fraction of Al_2O_3 particles in both materials. MA materials show very high stress compared with PM materials, while the ε_f of MA materials is very lower than that of PM materials. It is considered that the grain refinement by the milling treatment increase the proof stress of MA materials.

It is well known in the composites that one of the important strengthening mechanisms are the rule of mixture. To investigate the contribution of the rule of mixture to the composites, the elastic modulus of the composites was examined, and compared with the calculated results by the rule of mixture. The elastic modulus of the PM materials, E_c, is shown in **Fig.3**. Here, the broken lines are calculated by the rule of mixture expressed as follows;
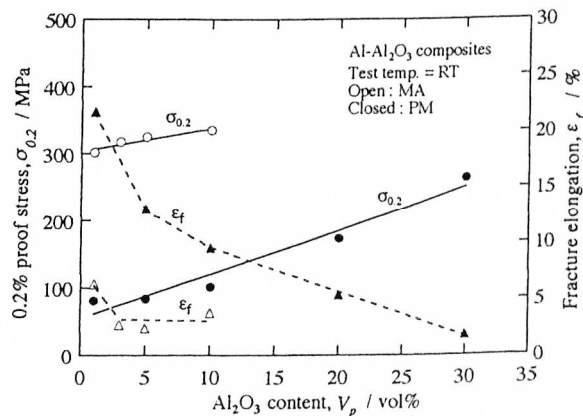

Fig.2   Dependence of 0.2% proof stress and fracture elongation of PM and MA materials on the volume fraction of Al_2O_3 particles.

$$E_c = V_m E_m + V_p E_p \quad (3)$$

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p} \quad (4)$$

where Eq.3 and Eq.4 show the upper and lower bound of the elastic modulus in the rule of mixture [12], V_m and V_p are the volume fraction of the matrix and the particles, and E_m and E_p are the elastic modulus of the matrix (72GPa) and the Al_2O_3 particle (370GPa), respectively. The E_c increases with increasing the Al_2O_3 particle content, and the experimental values are located between the upper and lower bound, however, the experimental results are very close to the lower bound curve. It can be suggested from the Fig.3 that the contribution of the strength of the particles to the strengthening of the composite is significantly low, and that $\sigma_c \doteqdot \sigma_m \doteqdot \sigma_p$.

It has been pointed out that the proof stress of particle reinforced composites is in proportion to the reciprocal of square root of the interparticle spacing [15,16]. The relation between $\sigma_{0.2}$ and the reciprocal of square root of interparticle spacing, $\lambda_s^{-1/2}$, in PM materials is shown in **Fig.4**. It is clear that there is no proportional relation between the both. It was the same in the relation between $\sigma_{0.2}$ and λ_s^{-1}. M.Vogelsang et al [17] have been observed the high dislocation density around SiC particles due to the large difference in the coefficient of thermal expansion between a ceramic particle and a matrix (CTE) after cooling from

Fig.3   Elastic modulus of the PM materials with various volume fraction of Al_2O_3 particle.
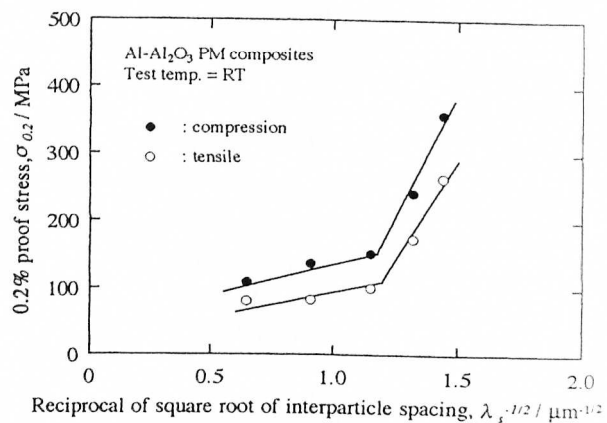
Fig.4   Relation between 0.2% proof stress and the reciprocal of square root of interparticle spacing.

annealing temperature. The high dislocation density region has been analyzed by C.T.Kim [18], and the radius of high dislocation density region is about two times as large as the radius of a particle. The volume fraction of high dislocation density region, V_{HD}, can be considered to be in proportion to the volume fraction of the particles when the particle size is a constant. The high dislocation region can be regarded as a work hardening region where flow stress is high compared with the other region. The work hardening region becomes large in proportion to the volume fraction of the particles, indicating that the proof stress of the composites linearly increases with the volume fraction, V_p (Fig.2). There is the considerable difference in the proof stress of Fig.4 and the proof stress in compression tests shows higher values than that in tensile tests, which indicates that the large difference in the thermal expansion between the particles and the matrix introduce tensile stress field into the matrix.

C. High temperature deformation properties

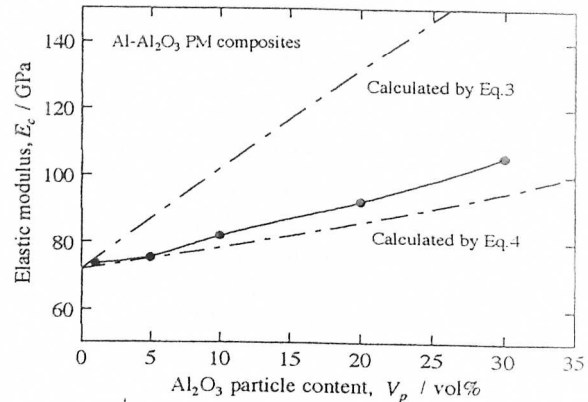The work-hardening at initial plastic deformation stage ($\sigma_{0.2}$-$\sigma_{0.02}$) at various temperatures is

shown in **Fig.5**. The amount of work-hardening decreases with temperature in the both materials. The work-hardening of MA materials is very higher than that of PM materials at lower temperatures, the difference in the work-hardening between the both materials decreases, and the dependence of the work-hardening on the Al_2O_3 content also decreases with the temperature. It is considered that the dislocation density in the high dislocation density region becomes low by the recovery and the recrystallization as the temperature increases so that the work hardening rapidly decreases.

The stress exponents (n value) of PM and MA materials were estimated by the stress-change tests. The stress exponents are 22.5 in PM and 22 in MA materials, these values are very high compared with the common Aluminum alloys (n=2-4). The apparent activation energy, Q, in both materials based on the n values is shown in **Fig.6**. The activation energies, Q are 236kJ/mol in PM and 223kJ/mol in MA materials, and these values are very high compared with the activation energy for self diffusion of Aluminum (142kJ/mol). The n and Q values are almost the same in the both, PM and MA materials.
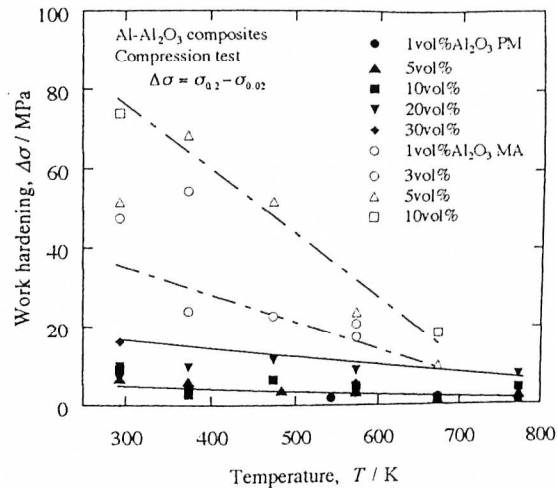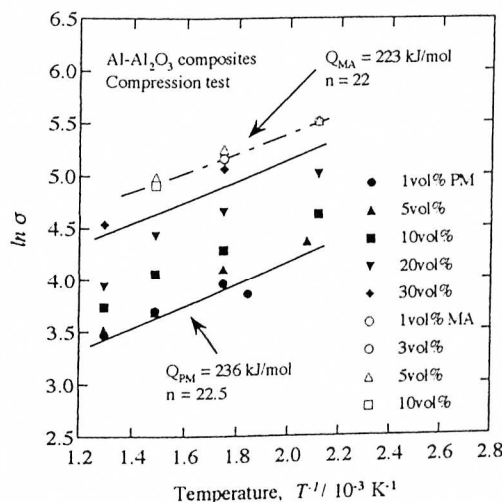

Fig.5　Dependence of work hardening on test temperature.

Fig.6　Dependence of the flow stress on temperature.

CONCLUSION

The deformation behavior and the strengthening mechanism of Al_2O_3 particle reinforced aluminum composites produced by powder metallurgy were investigated by the compression and tensile tests at various temperatures. Main results in this study are summarized as follows:

1) The proof stresses of PM and MA materials are linearly increased with the Al_2O_3 particle content. The flow stress of the MA materials is higher than that of PM materials because MA materials have very fine grains.

2) The elastic modulus of the composite is increased with increasing the Al_2O_3 particle content, however, the modulus is very close to the lower bound predicted by the rule of mixture. So it can be considered that the contribution of the strength of the particles to the strengthening of the composite is significantly low. The dominant factor of strengthening of the composite can be considered as the high dislocation area (work hardening region) in the vicinity of hard particles due to the difference in

thermal expansion between the Al_2O_3 particle and the aluminum matrix.

(3)   The stress exponents of PM and MA materials are n=22.5 and n=22, the apparent activation energies of PM and MA materials are 236kJ/mol and 223kJ/mol, respectively, and these values are very high compared with those of common Aluminum alloys.

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