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Mechanical Properties of Alumina Particle /Al-4.5mass%Cu Alloy Composites Fabricated by Transient Liquid Phase Sintering†

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Abstract

Preparation of Al_2O_3 particle/Al-4.5%Cu alloy composites was attempted by transient liquid phase (TLP) sintering. Al-4.5%Cu alloy was selected as the matrix phase for the TLP sintering, because it has the basic composition of durdumin.

As a result, in case of Al-4.5%Cu mixed powder, the microstructure after TLP sintering was composed of α-Al solid solution and $CuAl_2$(θ-phase) for any condition. In addition, the microstructure had Cu-poor phases in the vicinity of grain boundaries of α-Al solid solution. The morphology of the θ-phase formed at the grain boundary in the solid state sintered alloy was more continuous than in the TLP sintered alloy. The mechanical properties of the TLP sintered alloy were superior to the solid state sintered alloy. It was proved that the morphology of the θ-Phase formed at the grain boundary influenced the mechanical properties.

Effects of Al_2O_3 vol% on the sintering characteristics of the Al_2O_3 particle/Al-4.5%Cu alloy composites were examined. The mechanical properties of the TLP sintered composites were superior to those of the solid state sintered composites. It is clear that the bond strength between Al_2O_3 and the matrix plays an important role in the tensile strength of TLP sintered composites. It is also apparent that sintering processes of Al_2O_3/Al/4.5%Cu mixed powder were accelerated by TLP sintering.

KEY WORDS: (Transient Liquid Phase sinterin)(Aluminum matrix composite)(hot pressing)(Alumina,)($CuAl_2$)

1. Introduction

A large number of processes for producing particle reinforced Al alloy metal matrix composites have been examined, including conventional metallurgical processing techniques such as ingot metallurgy(I/M) or powder metallurgy(P/M)[1-2]. These process have both advantages and disadvantages. For example, the I/M methods use a simple process treatment, but it is difficult to control the interface reaction between reinforcement and metal by these method. On the other hand, the P/M methods have complex process treatments, but these methods depress the interface reaction between reinforcement and metal. In this study, the preparation of alumina particle/Al-4.5%Cu alloy composite was attempted by transient liquid phase(TLP) sintering which has the advantages of both I/M and P/M. Al-4.5%Cu alloy was selected as the matrix phase for the TLP sintering, because it has the basic composition of duralumin.

2. Experimental procedure

Atomized aluminum powder (99.8%) with an average size of 22μm, copper powder(99.8%) with an average size of 4μm and spherical alumina particles with an average size of 45μm were used for preparation of the composite by hot pressing. These were mixed by a vibrating ball-mill for 60s in air. The copper always constituted 4.5mass% of the metal constituents in each mixture while the percentage of alumina was adjusted so as to be 0,10,20 and 30 volume% the powder mixture.

The hot pressing of these powder mixtures was conducted in a vacuum. The hot pressings were carried out using pressures ranging from 53 to 93Mpa, and times ranging from 0.6 to 4.2ks. The Al-Cu system has a eutectic temperature of 821K[3]. The hot pressing temperatures were selected as 793K(i.e. 28K below the eutectic temperature), and 843K(i.e. 22K above the eutectic temperature). In this study, the materials which were

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pressed at 793K were called solid state sintered materials, and the materials which were pressed at 843K were called TLP sintered materials. The size of the cylindrical sintered materials were 10mm in diameter and about 20mm in height.

The microstructure of the sintered materials were investigated by density measurement, optical microscope, X-ray diffraction and electron probe micro-analysis (EPMA). Tensile tests were performed on samples machined from the mid-section of each sintered materials.

3. Experimental results and discussion

3.1 Preparation of Al-4.5%Cu alloy

Before the preparation of the composites, the characteristics of the Al-4.5%Cu matrix alloys were investigated. The results of X-ray diffraction have shown the sintered alloy were composed of α-Al solid solution and $CuAl_2$(θ-phase) for any condtions.

Fig.1 shows the results of EPMA analysis. The Cu-Kα images show the microstructures have copper poor zones in the vicinity of grain boundaries of α-Al solid solution. The θ-phase formed at the grain boundary in the solid state sintered alloy was slightly larger than that of the TLP sintered alloy.

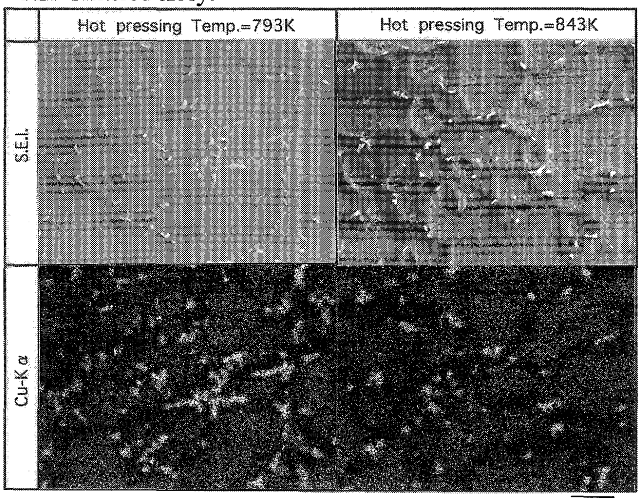

Fig. 1 EPMA analysis of Al-4.5%Cu alloy pressed at 793K and 843K for 1.8ks.

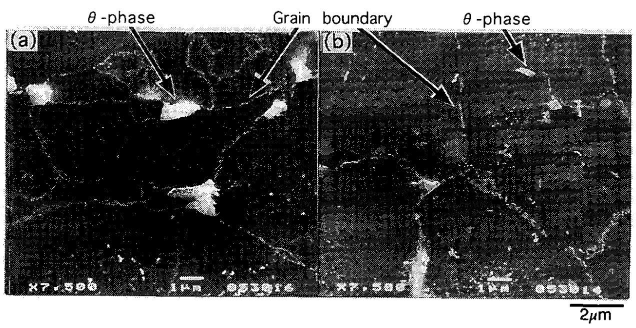

Fig. 2 Scanning electron micrographs of Al-4.5%cu alloy pressed at 763K(a) and 843K(b) for 1.8ks.

Fig.2 shows the SEM images in the vicinity of grain boundaries of α-Al solid solution. The θ-phase formed in the solid state sintered alloy was more continuous than that in the TLP sintered alloy.

The results of the tensile tests are shown in **Fig.3**. The tensile strength, the elongation and the reduction of area of the TLP sintered alloy are higher than for the solid state sintered alloy. The elongation and the reduction of area of the TLP sintered alloy are about equivalent to castings of the same composition. It was considered that the θ-phase at the grain boundary was the cause of the fracture. The discontinuously formed -phase at the grain boundary (Fig.2) ensured that the mechanical properties of the TLP sintering alloy were superior to the solid phase sintering alloy.

3.2 Preparation of Al_2O_3 particle / Al-4.5%Cu alloy composite

Preliminary experiments indicated the best conditions for preparation of Al_2O_3 particle/Al-4.5%Cu alloy composite in this work. The hot pressings were carried out using the pressure of 78Mpa, for times of 3.0ks.

The relationships between density and volume fraction of Al_2O_3 in Al_2O_3/Al-4.5%Cu composites are shown in **Fig.4**. The relative density was calculated from the theoretical density of Al-4.5%Cu alloy under the

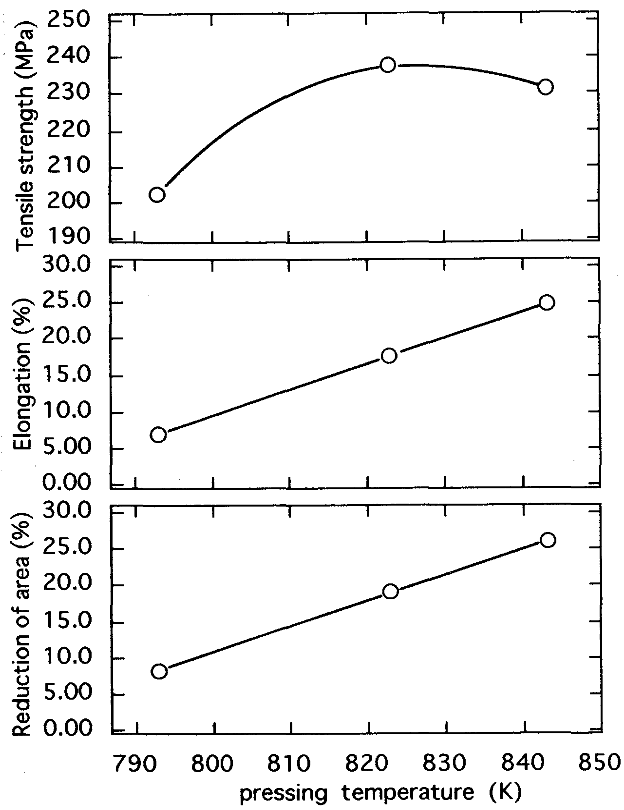

Fig. 3 Relationships between pressing temperature and the tensile properties of Al-4.5%Cu alloy pressed for 1.8ks.

assumption that all of the copper in the alloy contribute to the formation of the θ-phase. The densities increase with increasing volume fraction of alumina, but the relative densities are nearly constant. The density and the relative density of TLP sintered composites are smaller, more scattered and of higher value than for solid state sintered composites.

Fig.5 shows the SEM images of the Al_2O_3 particle/Al-4.5%Cu alloy interface of the composites. With the solid state sintered composites there are many vacancies in the interface, while for TLP sintered composites there are none. This microstructure indicates that the TLP sintered composites have a good bonding at the interfaces. Naka et al. reported that the best wettability between alumina and molten Al-Cu alloy was achieved in the Al-30mass%Cu alloy[4]. The phase diagram of Al-Cu system shows that the Al-28mass%Cu alloy has the greatest amount of the TLP in this study. The authors confirmed that the composition of the liquid phase formed during TLP sintering of the mixture of aluminum and copper powders was Al-37mass%Cu. These two compositions are of nearly the same value as in Naka's data. Therefore, the reason for good bonding between matrix and alumina is good wettability between liquid phase and alumina.

The results of the tensile tests are shown in **Fig.6** as a function of volume fraction of alumina. It is seen that tensile strength, elongation and reduction of area decrease with increasing volume fraction of alumina. The tensile properties of the TLP sintered composites were superior to solid state sintered composites. Wakil reported the extrusion of P/M composites in the semi-solid state using the almost the same composition in this work[5]. The value of tensile strength and elongation at 20 volume percent alumina in this work is about 15 times higher than Wakil's data.

SEM images of tensile fracture sections are shown in **Fig.7**. It is observed that the TLP sintered composites are characteristically more ductile than the solid state sintered composites. The brittle fracture and original surfaces of spherical alumina are observed in case of solid state sintered composites. The ductile fracture of the TLP sintered composites are exhibited by the dimples in the matrix and on the alumina surfaces. This result confirms the good bonding between matrix and alumina.

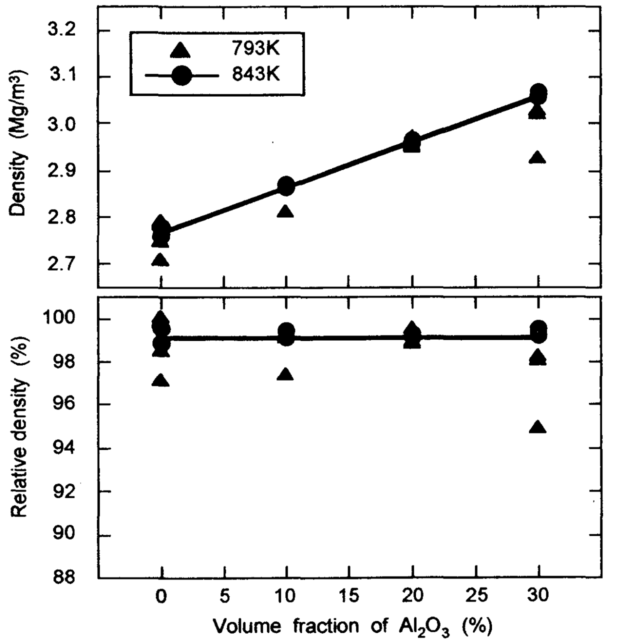

Fig. 4 The relationships between density and volume fraction of Al_2O_3 of Al_2O_3/Al-4.5%Cu composites.

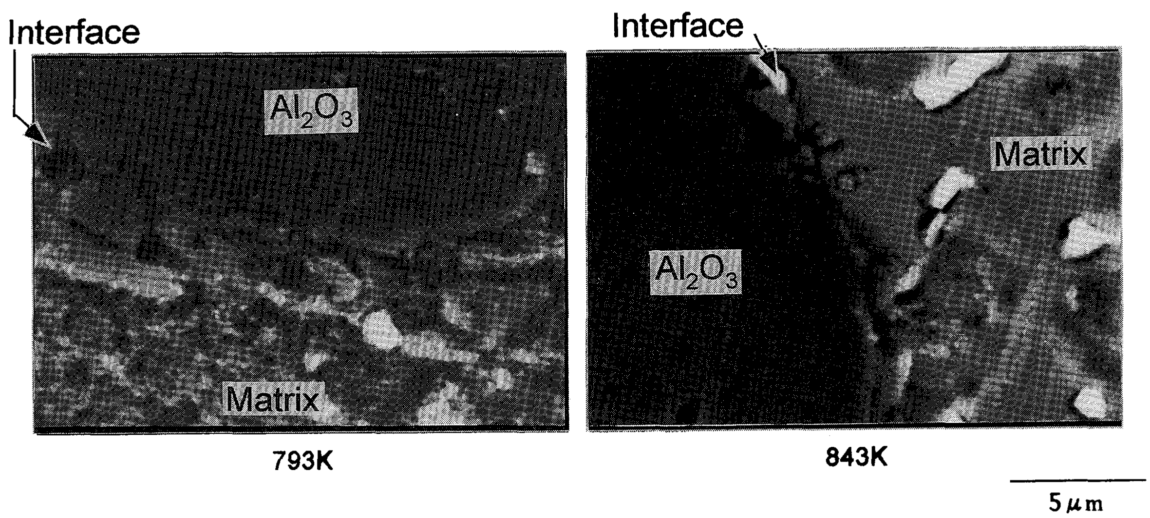

Fig. 5 COMPO images of Al_2O_3/Al-4.5%Cu composites pressed at 793K and 843K for 3.0ks.

3.3 Discussion of the strength of the Al_2O_3 particle /Al-4.5%Cu alloy composite

The values of the estimated strength are obtained on the following assumptions for the strength of the Al_2O_3 particle/Al-4.5%Cu alloy composites. The assumptions are as follows.

1) The composites are homogeneous.

2) When exfoliation occurred at the Al_2O_3/matrix interface, its region is considered to be void

3) When the Al_2O_3 particle fractured, the strength of its region is equal to that of the matrix.

4) The Al_2O_3 particle does not strengthen the composites.

The estimated strengths are obtained from the following equations.

$$A_f=(x^2-F_f\pi(d/2)^2)/x^2 \quad (1)$$

$$S_e=A_fS_M \quad (2)$$

where A_f is fraction of effective area, S_e is the estimated strength, x is interparticle distance, F_f is the exfoliation fraction at the Al_2O_3/matrix interface(this is obtained by SEM observation), d is diameter of the Al_2O_3 particle, S_M is the strength of the matrix. This is determined from the tensile strength of 0vol% Al_2O_3/Al-4.5%Cu composites.

Then $x=d(\pi/6V_f)^{1/3}$ [6], where V_f is the volume fraction of Al_2O_3. That is to say, the effective area denotes that the exfoliation area at Al_2O_3/matrix interfaces of the composites is to be taken from the cross sectional area. The gaps in the results for the tensile tests and the estimated strength from the above equations reflect the bonding strength between Al_2O_3 and matrix alloy. That is to say, if the experimental value exceeds the estimated value, the composites have good bonding between matrix and Al_2O_3. When the experimental value is lower than the estimated value, the composites have bad bonding between matrix and Al_2O_3. Furthermore, it is thought that the existence of Al_2O_3 particles causes the fracture of composites.

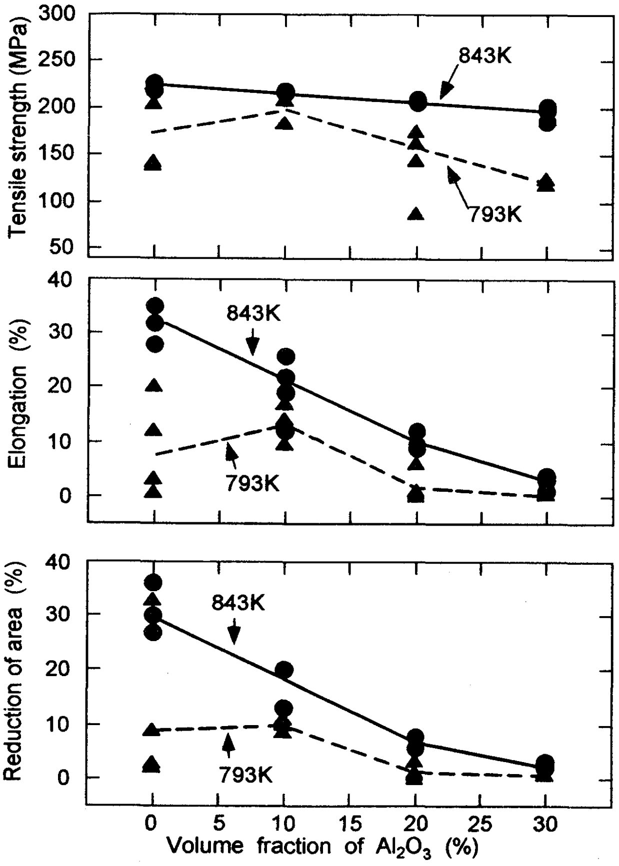

Fig. 6 Relationships between volume fraction of Al_2O_3 and the tensile properties of Al_2O_3/Al-4.5%Cu composites pressed at 793K and 843K.

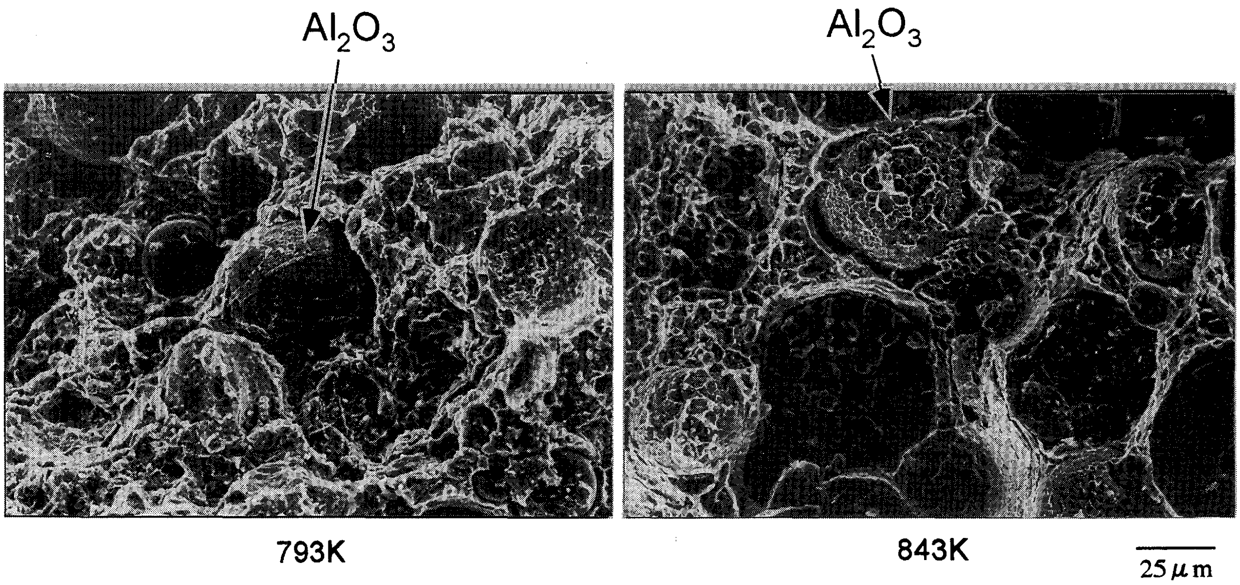

Fig. 7 Scanning electron micrographs of tensile fracture surfaces for 30vol%Al_2O_3/Al-4.5%cu composites pressed at 793K and 843K for 3.0ks.

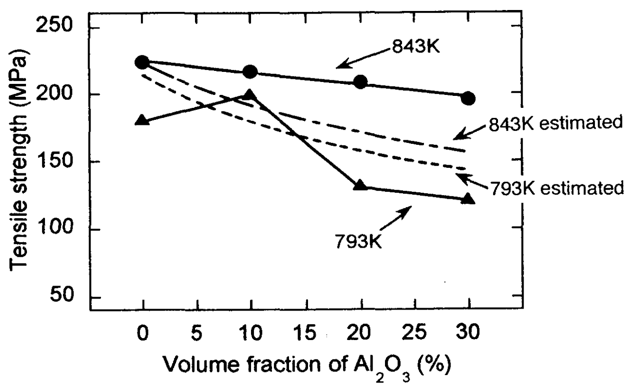

Fig. 8 Comparison of the estimated value and experimental value of tensile strength in Al_2O_3/Al-4.5%Cu composites.

Fig.8 shows the comparison of the estimated values and experimental values of tensile strength in Al_2O_3/Al 4.5%Cu composites. The tensile strength decreases with increasing volume fraction of Al_2O_3. The same tendency is noticed with the experimental values and estimated value of solid state sintered composites. On the other hand, the decrease in value of the experimental value plots is smaller than that of the estimated values in the case of TLP sintered composites.

when the experimental value equals the estimated value, the bonding strength between Al_2O_3 particle and matrix are expressed by the following equations.

$$S_I = (S_e - A_f S_M)/(1 - A_f) \quad (3)$$

where S_I is bonding strength between Al_2O_3 particle and effective area, S_M is strength of the matrix. The bonding matrix, S_e is the estimated strength, A_f is the fraction of strength between Al_2O_3 particle and matrix is estimated 130Mpa. This value is close to Iseki's data(60-90Mpa)[7] that is the bonding strength between alumina and Al-4.0%Cu of alumina/Al-4.0%Cu alloy composites. Therefore, it is considered that the improvement of bonding strength between Al_2O_3 particles and the matrix alloy causes the small decrease of experimental value in the plots for TLP sintered composites.

4. Conclusions

1) The microstructures of Al-4.5%Cu alloy prepared by this study consisted of α-Al solid solution and $CuAl_2$(θ-phase) in all condtions. In addition, the microstructure had a Cu-poor zone in the vicinity of grain boundaries of α-Al solid solution.
2) The form of θ-phase formed at the grain boundary of the solid phase sintering alloy were more continuous than that of the TLP sintering alloy. The mechanical properties of the TLP sintering alloy was superior to the solid phase sintering alloy. It was apparent that θ-phase, formed at the grain boundary, affected the mechanical properties.
3) The mechanical properties of the TLP sintering composites were superior to solid phase sintering composites. It is clear that the bonding strength between Al_2O_3 and matrix plays an important role for tensile strength of the TLP sintering composites. The sintering process of Al_2O_3/Al/4.5%Cu mixing powder was also accelerated by TLP sintering.

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