Microstructure and Hardness Characteristics of Al$_2$O$_3$-B$_4$C Particle-Reinforced Cu Matrix Composites

K.E. Öksüz[a,*] AND Y. Şahin[b]

[a]Department of Materials and Metallurgy Engineering, Cumhuriyet University, Sivas, Turkey

[b]Department of Manufacturing Engineering, Faculty of Technology, Gazi University, Ankara, Turkey

Copper is widely used in industrial applications because of its high electrical and thermal conductivity, easiness of processing and good corrosion resistance. However, copper also has some distinct limitations such as low hardness, low tensile yield strength and poor creep resistance. In this report copper matrix was reinforced with ceramics like Al$_2$O$_3$ and B$_4$C particles using powder metallurgy (PM) method and its microstructure was examined with SEM and EDS. The microstructure has revealed an uniform distribution of particles in the matrix and a good interface bonding between B$_4$C particles and the matrix. However the dispersion of Al$_2$O$_3$ particles, of larger sizes, has led to some porosity and inter-particle contacts in the composites. Therefore, hardness of B$_4$C particle-reinforced composites is significantly higher than that of Al$_2$O$_3$ particle-reinforced composites.

1. Introduction

Since copper-based materials have a relatively low wear resistance and high-temperature strength, the copper matrix has been successfully strengthened with graphite particles, discontinuous or continuous fibres, called metal matrix composites (MMCs). The incorporation of ceramic particulate reinforcement can significantly improve the high-temperature mechanical property and wear resistance, without severe deterioration of thermal and electrical conductivity of the matrix [1]. Therefore, these kinds of materials are considered to be promising candidates for applications, where high conductivity, high mechanical property and good wear resistance are required. SiC particle-reinforced Cu composites are prepared using different methods and studied in terms of the effects of particle size, content and distribution [2–3]. A considerable attention is focused on Al$_2$O$_3$ particle-reinforced Cu composites due to high strength and temperature stability, however other particles like B$_4$C, TiB$_2$ have been poorly investigated. The above review shows that there are reports on the mechanical behaviour of SiC/Cu [4–9] and Al$_2$O$_3$ [10–17], but a limited study on the microstructure of B$_4$C-Cu composites has been conducted. The purpose of the current study, therefore, was to produce copper-matrix-based composites and to evaluate their microstructure, hardness and density.

2. Materials and methods
2.1. Materials

In order to produce Al$_2$O$_3$-Cu and B$_4$C-Cu-matrix-based composites, commercial Cu powders produced by PM method, with an average particle size of 45 μm with

99.5% purity were acquired. B$_4$C and Al$_2$O$_3$ powder with particle sizes of $\leq$ 10 μm and with 99+% purity, were used for preparation of composites.

Prepared composites, hereafter donated as Al$_2$O$_3$/Cu matrix composites and B$_4$C/Cu matrix composites, were containing about 10 volume percent (vol.%) of particles. The mixture of powders was uniaxially cold compacted. The samples were gradually heated up to 880 °C and kept for 1.5 h at that temperature. The sectioned samples were examined by SEM. Density of composites was obtained by the Archimedean principle. Hardness of the composites and of the matrix alloy were measured by Rockwell B hardness method (60 kg) after polishing to a 3 μm finish and the mean value of at least five readings was taken.

3.Results and discussion
3.1. Microstructure

Figure 1a shows the SEM micrograph of a commercial copper matrix sintered at 880 °C for 1.5 h. The copper matrix microstructure is formed by non-uniform grains with very different sizes. The grain boundaries can be clearly seen. The average grain size is about 10–25 μm. A few pores are seen in the SEM image as dark spots. The pores have irregular shape and are arbitrarily oriented. Their size, based on the relative distribution of porosity and the obtained statistical data, varied in the range from 1 μm to 7 μm. Oxygen is almost insoluble in copper and forms Cu$_2$O interdendritic eutectic upon solidification. EDS analysis of the matrix is shown in Fig. 1b, which reveals that there is about at 99.14 wt.% of Cu and about 0.83 wt.% of oxygen, due to applied high temperature during the production stage. Figure 1c shows the micrograph of a 10 vol.% Al$_2$O$_3$ particle-reinforced copper composite sintered at 880 °C for 1.5 hours. The Al$_2$O$_3$ particles were found to be angular in shape, with size of about 5 μm. The distributions of Al$_2$O$_3$ particles in the matrix seemed to be

*corresponding author; e-mail: kerimemreoksuz@gmail.com
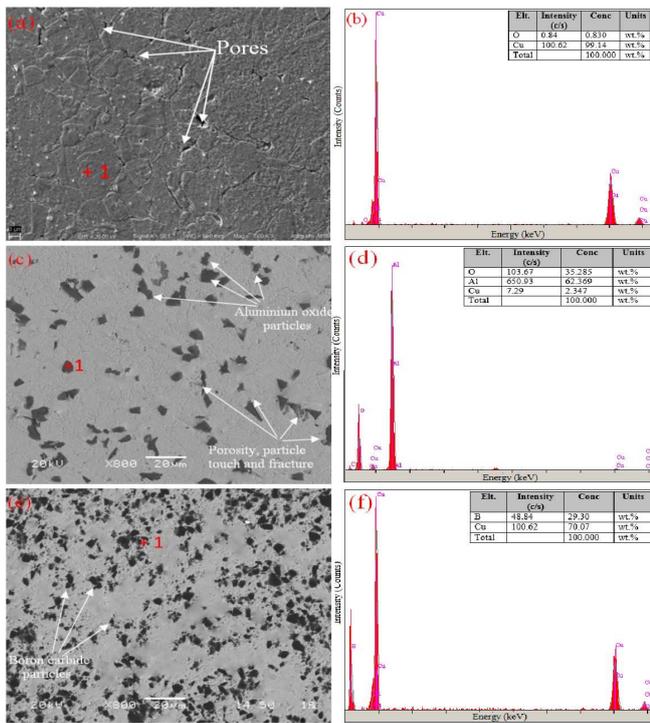
Fig. 1. Microstructure of the particle-reinforced composites. (a) Copper matrix, (b) EDS analysis of matrix, (c) Al_2O_3 particles, (d) EDS analysis of Al_2O_3 particles, (e) B_4C particles, (f) EDS analysis of B_4C particles.

uniform. Point 1 indicates alumina particle in Cu matrix (Fig. 1d). The grain size of the copper matrix can be clearly observed. In addition, the composite had contained a small amount of pores in the matrix. As reported in many research articles, the wettability of copper and SiC particles [4–5] was weak, leading to a high volume of porosity [12–13]. It might be concluded that apart from these multiple strengthening mechanisms, the porosity had a significant influence on the tribological properties [5]. Figure 1e shows the SEM micrograph of a 10 vol.% B_4C particle-reinforced Cu matrix composite sintered at the same conditions. The B_4C particles can be observed as black spots in this micrograph. It could be seen that these powders had a certain shape viz. polygonal geometry. The distributions of B_4C particles in the matrix seemed to be more uniform when compared to the previous microstructure of Al_2O_3 particles. Average dimensions of B_4C particles was less than 8 μm, but apart from large B_4C particles, fine B_4C particles are presented in the micrograph. There is no evidence of the presence of cavities neither at interface nor in the matrix, which is due to generation of enough adhesion bonding between the particles and the copper matrix. The bonding strength at the interface between Cu and B_4C particles seems to be higher than the bonding strength between Cu and Al_2O_3 particles. Consequently, B_4C particles were effectively dispersion strengthened by the matrix. Characterization of the obtained powders shows that the size of individual particles was rather small,

i.e. approximately 3–6 μm. They had high surface energy level because of their small sizes. Figure 1f shows EDS analysis of B_4C-Cu matrix composites. At location of point 1 content of Cu was about 70.07% and content of B was about 29.30%.

3.2. Density and hardness of composites

Density and hardness of both types of MMCs are shown in Figs. 2a and b, respectively. The density of composites decreases slightly in comparison with matrix, with the addition of ceramic particles. The average values of density of Cu, Cu+10 vol.% Al_2O_3 and Cu+10 vol.% B_4C compacts were about 7.97, 7.26 and 7.654 $\mathrm{g\,cm^{-3}}$, respectively. These corresponded to
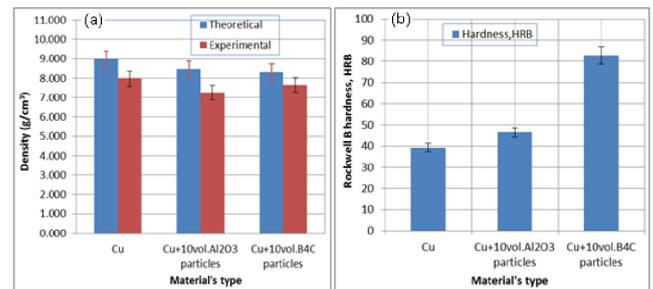
Fig. 2. Density (a) and hardness (b) of Cu matrix particle-reinforced composites.

87.72, 83.49 and 85.96% of relative density in comparison with the theoretical density, which shows that the densification by cold pressing of prealloyed powders was not completely terminated, this result is shown within a 5% error bar. The reason for such an inadequate consolidation could be also related to the copper matrix strengthening and dislocation generation by Al_2O_3 particles as well as the particle size, and shape of the powders [14]. Hardness of the materials is a physical parameter showing the ability of resisting local plastic deformation. Hardness of composites increased considerably with the introduction of particles and with changing the particle type and size, as shown in Fig. 2b with 5% error bar. Hardness has increased from 39.2 HRB, 46.40 HRB to 82.20 HRB for the Cu matrix, 10 vol.% Al_2O_3 particle-reinforced MMCs and 10 vol.% B_4C particle-reinforced MMCs, respectively. This might be due to presence of finer B_4C particles and achievement of enough bonding between Cu matrix and particles. Namely, strengthening of the copper was achieved by dispersion strengthening, due to the dispersion of much finer grain size of B_4C powders in the matrix in a more effective way, which became the obstacles for the movement of dislocations when the plastic deformation occurred. Thus, the improvement of hardness was about 109.6% for B_4C particle composite while the increase was about 18.46% for Al_2O_3 particle composite in spite of the high hardness of Al_2O_3 grains. Appearance of pores in the composite reinforced with Al_2O_3 has resulted in the weaker bonding strength of the

Al$_2$O$_3$ particle and matrix (Figs. 2a,b). The reduction of the porosity and grain size was the cause of obtaining the fine microstructure for B$_4$C particle composite, while consolidation pressure seemed to be not enough for Al$_2$O$_3$ particle composite. As it is well known, the hardness of ductile copper was improved by dispersion of second hard phase [4, 5, 16]. The results indicate that Cu-SiC composite with 30 μm particle sized SiC had superior properties than the Cu-SiC composite with 1 μm particle sized SiC, which is not the case for the present study.

Another study indicated that the hardest specimen was obtained for the Cu-5 wt.% SiC (20 μm) reinforced composite, while its hardness was dropped dramatically when the content of SiC exceeded 5 wt.% [3]. However, the hardness of Cu-SiC (110 μm) reinforced composite had increased with the SiC content. The plastic flow was impeded more strongly with the increase of the SiC content. Another study showed that the average micro-hardness of pure copper was measured to be 70 HV [15]. However, Cu-Al$_2$O$_3$ composite was characterized by low increase in the grain size and by low decrease in the micro-hardness [16]. Hardness and porosity of uncoated 10 vol.% SiC/Cu composite and nickel coated SiC(Ni)/Cu composite were found to be about 78.1 HB, 84.6 HB and 1.4, 0.9, respectively [2]. It seemed to be understandable that the high hardness was due to the lower size of particles and good interface bonding of B$_4$C particles.

4. Conclusions

Study of copper based MMCs containing 10 vol.% Al$_2$O$_3$ and B$_4$C particles produced by PM method shows that hardness and density of composites changes with the type of particles. The presence of Cu, Al$_2$O$_3$ and B$_4$C was verified by EDS analysis. SEM observations of the microstructure has shown a more homogeneous distribution in the matrix for B$_4$C particles than for Al$_2$O$_3$ particles. Thus, hardness of composites increased considerably with addition of B$_4$C particles when compared to the matrix and Al$_2$O$_3$ particle-reinforced composite, which is due to using a smaller sizes of powder grains and achievement of enough interface bonding between the particles and matrix. In the case of Al$_2$O$_3$ particles the pores has formed between the particle and matrix, which resulted in lower hardness. As a result, dispersion of finer grain size B$_4$C particles in the matrix was more effective than dispersion of the Al$_2$O$_3$ particles in the copper matrix.

References

[1] D.B. Miracle, *Comp. Sci. Technol.* **65**, 2526 (2005).

[2] Y. Zhan, G. Zhang, *Mater. Lett.* **57**, 4583 (2003).

[3] G.Ç. Efe, I. Altinsoy, M. Ipek, S. Zeytin, C. Bindal, *Acta Phys. Pol. A* **121**, 251 (2012).

[4] T.P. Sathishkumar, S. Satheeshkumar, J. Naveen, *J. Reinf. Plast. Comp.* **33**, 1258 (2014).

[5] Y.C. Lin, H.C. Li, S.S. Liou, M.T. Shie, *Mater. Sci. Eng. A* **373**, 363 (2004).

[6] A. Brendel, C. Popescu, C. Leyens, J. Woltersdorf, E. Pippel, H. Bolt, *J. Nucl. Mater.* **329–333**, 804 (2004).

[7] M. Barmouz, M.K.B. Givi, *Composites Part A: Applied Sci. Manufacturing* **42**, 1445 (2011).

[8] M. Barmouz, P. Asadi, M.K. Besharati Givi, M. Taherishargh, *Mater. Sci. Eng. A* **528**, 1740 (2011).

[9] M. Gupta, M.O. Lai, C.Y. Soo, *Mater. Sci. Eng. A* **210**, 114 (1996).

[10] S.F. Moustafa, Z. Abdel-Hamid, A.M. Abd-Elhay, *Mater. Lett.* **53**, 244 (2002).

[11] V. Rajković, A.D. Božić, E. Devečerski, S. Bojanić, M.T. Jovanović, *Revista De Metal.* **46**, 520 (2010).

[12] M. Korac, Z. Kamberovic, Z. Andic, M. Filippovic, M. Tasic, *Sci. Sinter.* **42**, 81 (2010).

[13] F. Shehata, M. Abdelhameed, A. Fathy, M. Elmahdy, *Open J. Met.* **1**, 25 (2011).

[14] D.W. Lee, B.K. Kim, *Mater. Lett.* **58**, 378 (2004).

[15] P.K. Jena, E.A. Brocchi, M.S. Motta, *Mater. Sci. Eng. A* **313**, 180 (2001).

[16] S.J. Hwang, *J. Alloy. Compd.* **509**, 2355 (2011).

[17] J.P. Stobrawa, Z.M. Rdzawski, W.J. Gluchowski, *J. Nanosci. Nanotechn.* **12**, 9102 (2012).