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EFFECT OF MATRIX STRENGTH ON THE PLASTIC BEHAVIOR OF BMG/CRYSTALLINE COMPOSITES IN SUPERCOOLED LIQUID REGION

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Abstract. The crystalline matrix - bulk metallic glass (BMG) particle composites having two different matrix strengths were manufactured by electroless plating of copper and nickel on BMG powder and subsequent consolidation. The plastic behavior of composites was determined by the uniaxial compression test in the supercooled liquid region of BMG. The localization of the deformation in the soft matrix strongly lowers the flow stress in the composite containing a soft matrix. A homogenous deformation was obtained in the composite having the matrix strength close to the BMG strength. The strain state in the composites was interpreted by the finite element method simulation.

1. INTRODUCTION

Bulk metallic glass (BMG) alloys can homogenously deform in the supercooled liquid region since BMG alloys exhibit Newtonian flow at temperatures in this region (e.g. [1,2]). BMG/crystalline composites can also deform homogenously in the supercooled liquid region as reported in our previous work [3]. However, the effect of crystalline matrix strength on the deformation behavior of the BMG/crystalline composites in the supercooled liquid region of BMG has seldom been reported.

In the present work, BMG/crystalline composites containing 35% by volume of crystalline matrixes were produced and the deformation behavior of these composites was determined by the uniaxial compression test. In order to interpret the evolution of strain states during compression, the finite element method (FEM) simulation was performed in the idealized BMG/crystalline composites.

2. EXPERIMENTAL PROCEDURE

BMG powder of $Cu_{54}Ni_{6}Zr_{22}Ti_{18}$ was produced by a high pressure gas atomization [4]. To synthesize the composite powder containing 35 vol.% of crystalline phase, electroless coating of copper (Cu) and nickel (Ni) containing 3 atomic % of phosphorus on the BMG powder with size ranging from 63 to 90 μm was carried out. Two BMG composite samples, one containing Cu and the other with Ni were produced by spark plasma sintering. The samples containing 35 vol.% of Cu and Ni are hereafter referred to as BMG-Cu and BMG-Ni, respectively.

The deformation behavior of BMG/crystalline composites was measured at 723K under a compressive mode using a Gleeble tester (System 3500). The evolution of strain states of BMG/crystalline composites during the uniaxial compression was simulated with the commercial FEM package DEFORM™-2D.

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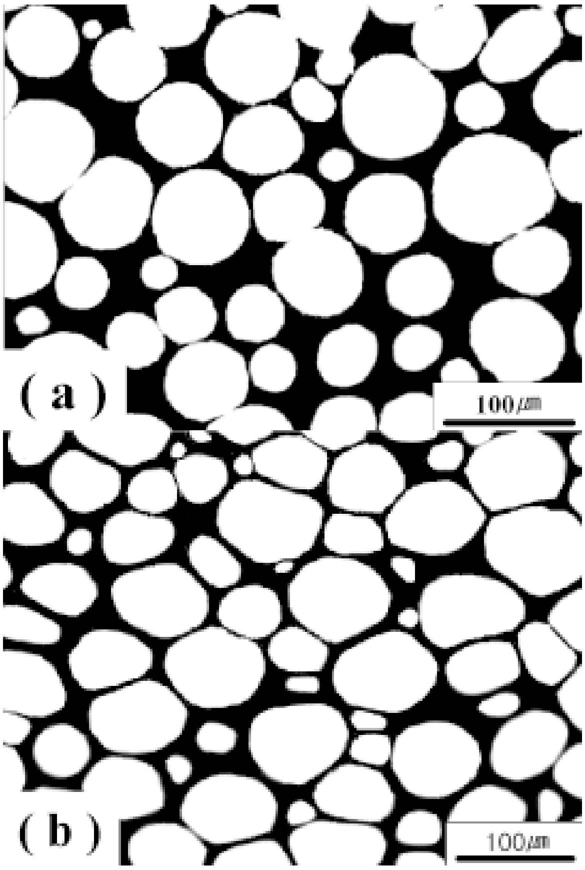

Fig. 1. Optical microstructures observed from the transverse direction of the samples after the SPS consolidation. (a) BMG-Cu, (b) BMG-Ni.

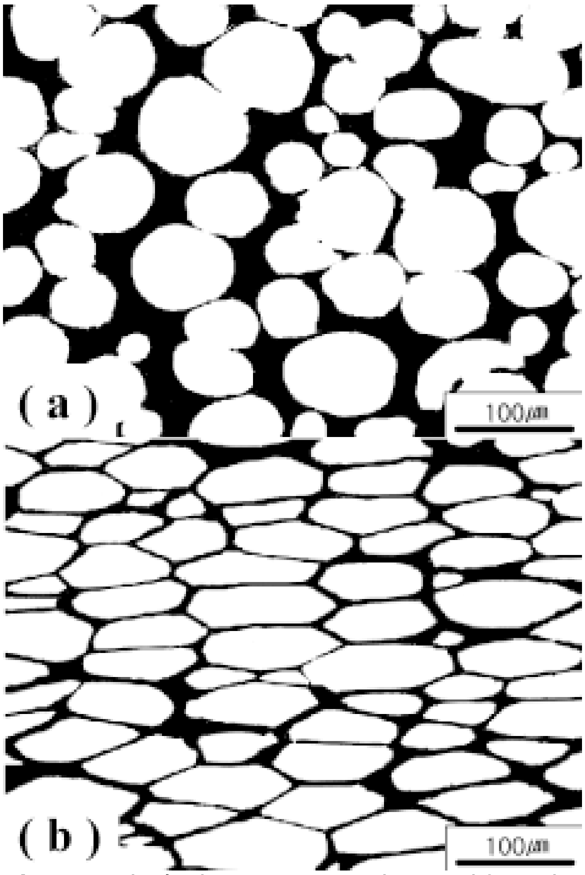

Fig. 2. Optical microstructures observed from the transverse direction of the samples after compression to ε=0.69 at 723K. (a) BMG-Cu, (b) BMG-Ni.

3. RESULTS AND DISCUSSION

As mentioned above, the composites were consolidated by spark plasma sintering (SPS) using the BMG powder coated with Cu or Ni. Results obtained by XRD and DSC indicate that crystalline Cu and amorphous Ni were coated on the BMG powder. During SPS in the supercooled liquid region of BMG, coated amorphous Ni crystallized, while no crystallization occurred in BMG particles.

Fig. 1 shows the microstructure of the BMG/crystalline composites after SPS. A proper etching reveals separately BMG particles (unetched white area) and crystalline phases (etched dark area) in the composites. After SPS, the composites display BMG particles embedded in the Cu or Ni matrix. During SPS, the movement and deformation of powder gives rise to the consolidation. Interestingly, the deformation mainly took place in outer coated Cu and Ni layers and the deformation of inner BMG particles was very limited, which led to the formation of the microstructure as shown in Fig. 1. The original spherical shape of BMG particles was still preserved in BMG-Cu (the sample containing 35 vol.% of Cu). A small change in the shape of BMG particles in BMG-Ni (the sample comprising 35 vol.% of Ni) was attributed to some contribution of BMG particles to the consolidation.

In contrast to the evolution of similar microstructures in the BMG-Cu and BMG-Ni composites after SPS, markedly different microstructures were observed in the composites after uniaxial compression. Fig. 2 shows the microstructures observed from the samples after compression at 723K to 50% reduction in thickness (corresponding strain of ε=0.69). The loading directions were the top and the bottom in the microstructure. In BMG-Cu, the BMG particles deformed only slightly and the distance between the BMG particles in the compres-

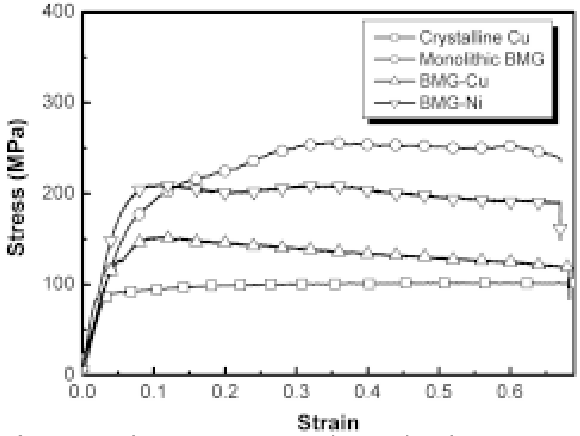

Fig. 3. Strain-stress curves determined at 723K at the strain rate of $2{\cdot}10^{-3}$/s.

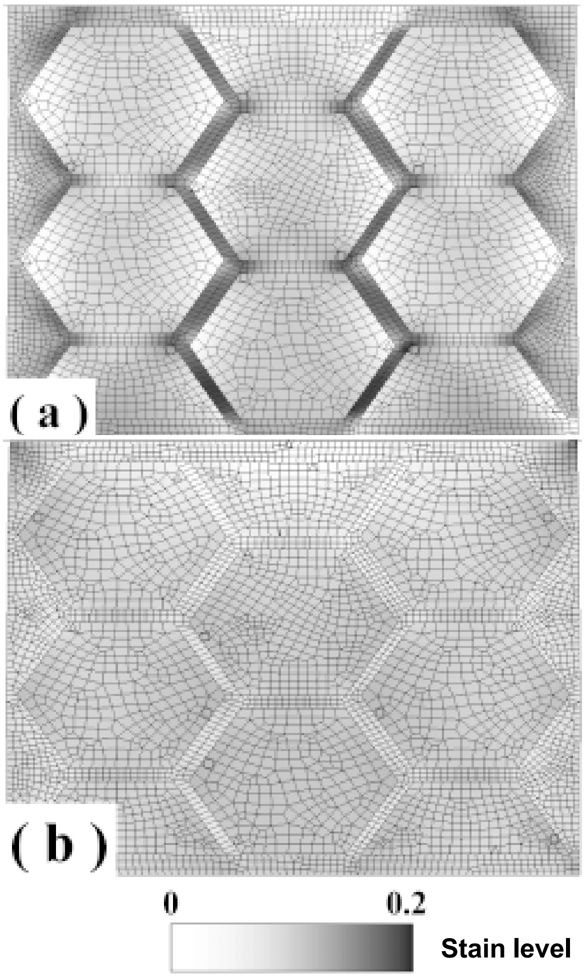

Fig. 4. FEM results showing the distribution of effective strain in the idealized BMG/crystalline composites having a matrix with (a) 40%, (b) 80% strength of BMG.

sion direction was much closer than that in the perpendicular direction. This fact indicates that the deformation mainly took place in the matrix Cu, while the BMG particles hardly deformed. Unlike BMG-Cu, an extensive deformation of the BMG particles was observed in the BMG-Ni sample after compression. The mean aspect ratio defined as the ratio of width-to-height of the BMG particles in the cross section was about 3.1 corresponding to a strain of ε=0.54 which is close to the strain ε=0.69 imposed on the outer sample. Thus, it is noted that the BMG particles deformed fairly homogenous with the crystalline Ni in the BMG-Ni composite.

Compression tests of the composites along with a monolithic BMG sample and a crystalline pure Cu sample were performed in a Gleeble tester at 723K. The duration of heating, holding and compression test were kept within the onset time for crystallization of BMG. DSC results confirmed that no crystallization of BMG occurred during compression. Fig. 3 shows compressive stress-strain curves determined at the strain rate of $2{\cdot}10^{-3}$/s. At 723K, the monolithic BMG sample displayed homogeneous plastic flow, the flow stress reached the maximum of 235 MPa at ε=0.4 and remained nearly unchanged until ε=0.69. The crystalline Cu sample had a uniform flow stress of 90 MPa during compression reflecting that softening equilibrates hardening at 723K. The BMG-Cu composite displayed the peak stress of 140 MPa at ε=0.08 and a gradual softening with increasing strain. In the BMG-Ni composite, a quite similar level of the flow stress of 200 MPa was obtained at strains ε>0.1.

Fig. 3 indicates that the flow stress of the crystalline Cu is about 40% of that of BMG at 723K. It is interesting to note that the flow stress of the BMG-Cu composite is much lower than that predicted by the mixture rule. As is readily seen in Fig. 2a, the localization of the deformation in the soft Cu matrix obviously lowers the flow stress in this composite. The strength of Ni containing 3 atomic % of phosphorous at 723K was not measured in this experiment. However, the mixture rule implies that the strength of the matrix Ni should be above 80% of that of BMG.

In order to interpret this result, the evolution of the strain states of the BMG/crystalline composites was simulated with the FEM calculation. In the simulation, idealized composites having different matrix strengths were assumed. Fig. 4 shows the distribution of effective strain at an imposed compressive strain of ε=0.1. High strains are strongly localized in the matrix of the composite having a matrix with 40% strength of BMG, while a fairly uniform distribution of strains prevails in the composite having a matrix with 80% strength of BMG. Accordingly, the matrix strength of the crystalline phase should be close to that of BMG in order to obtain a homogenous deformation of the BMG/crystalline composite in the supercooled liquid region of BMG.

4. CONCLUSIONS

The crystalline matrix - bulk metallic glass (BMG) particle composites having two different matrix strengths were produced and the deformation behavior of these composites was determined in the supercooled liquid region of BMG. Because of the localization of the deformation in the soft matrix, the flow stress in the composite containing a soft matrix was lower than that expected from the mixture rule. The matrix strength of the crystalline phase should be close to that of BMG in order to obtain a homogenous deformation of the BMG/crystalline composite.

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