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Wear behavior of Fe-based bulk metallic glass composites

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ABSTRACT

Composite samples comprising Fe-based metallic glass particles and the crystalline Ni matrix were produced. Wear behavior was investigated by a pin-on-disc type tester using hardened steel as the counter material. It was concluded that the wear mechanism depended on the volume fraction of crystalline nickel in the composites. The transition from the brittle fracture to the adhesive wear was observed by increasing the volume fraction of ductile Ni in the composites.

1. Introduction

Owing to the high strength and hardness of bulk metallic glass (BMG) alloys, BMG alloys exhibit a superior wear resistivity that provides potential for application in friction parts for severe wear conditions [1,2].

The wear behavior of BMG alloys is commonly distinguished from that of crystalline materials [3–5]. Since BMG alloys are extraordinarily hard and brittle in nature, deformation and cracking occur through localized shear bands [3,4]. Furthermore, crystallization of BMG alloys can take place during the wear process, which leads to a brittle fracture at the worn surface [5].

The formation of fine second-phase particles in BMG composites often improves wear resistance because these particles effectively block the propagation of shear bands formed in the brittle amorphous matrix [6,7]. Our previous work [8–10] reported that artificial BMG composites comprising BMG particulates in the crystalline matrix were produced by powder consolidation. It is expected that the composition of the BMG alloy and crystalline matrix has a strong impact on the wear behavior of these artificial BMG composites.

In this work, we investigated the wear behavior of BMG composites having various fractions of the BMG alloy and crystalline phase. For this purpose, the composite powder comprising inner Fe-based metallic glass particles and outer nickel shells was first produced by electroless plating. Subsequently, the composite powder was consolidated by spark plasma sintering to produce the composite samples. The wear behavior of the BMG composites was investigated using a dry sliding wear test.

2. Experimental procedure

Metallic glass (MG) powder with a nominal composition of $Fe_{61.5}Cr_{11.5}Al_{1.03}Si_{2.64}P_{4.34}C_{7.72}Mo_{1.45}Mn_{0.84}B_9$ (at.%) was produced by high-pressure gas atomization in a closed system [11]. MG powder ranging in size from 15 to 30 μm was screened and used for this experiment. The composite powder comprising inner MG particles and outer nickel (Ni) shells was produced by electroless plating. In the composite powder, the volume fraction of crystalline Ni was controlled by the thickness of the coated layer.

The composite powder was consolidated in the supercooled liquid region (SLR) of the MG alloy by means of spark plasma sintering to produce bulk composite samples comprising MG particles in the crystalline Ni matrix. The rod samples containing 50, 70, 80, 90, 95, and 100 vol.% of MG are hereafter referred to as samples Ni/50MG, Ni/70MG, Ni/80MG, Ni/90MG, Ni/95MG, and Ni/100MG, respectively.

Wear tests were conducted using a pin-on-disc (ASTM G99) wear testing machine, which was used with composite samples of 5 mm in diameter sliding against a hardened steel disc with a hardness of H_RC 63. Before the wear test, the average surface roughness, R_a, of the specimen and disc was about 0.20 μm.

3. Results and discussion

As mentioned previously, composite samples were produced through the consolidation of the composite powder comprising inner MG particles and outer Ni shells. Fig. 1 shows the optical micrographs of the transverse sections of (a) Ni/90MG and (b) Ni/70MG composites after consolidation. The samples in the microstructure were compressed from the top and bottom during SPS. Pore-free composites display MG particles (bright contrast) embedded homogeneously in the crystalline Ni matrix (dark contrast). It is expected that the Ni matrix hinders the propagation

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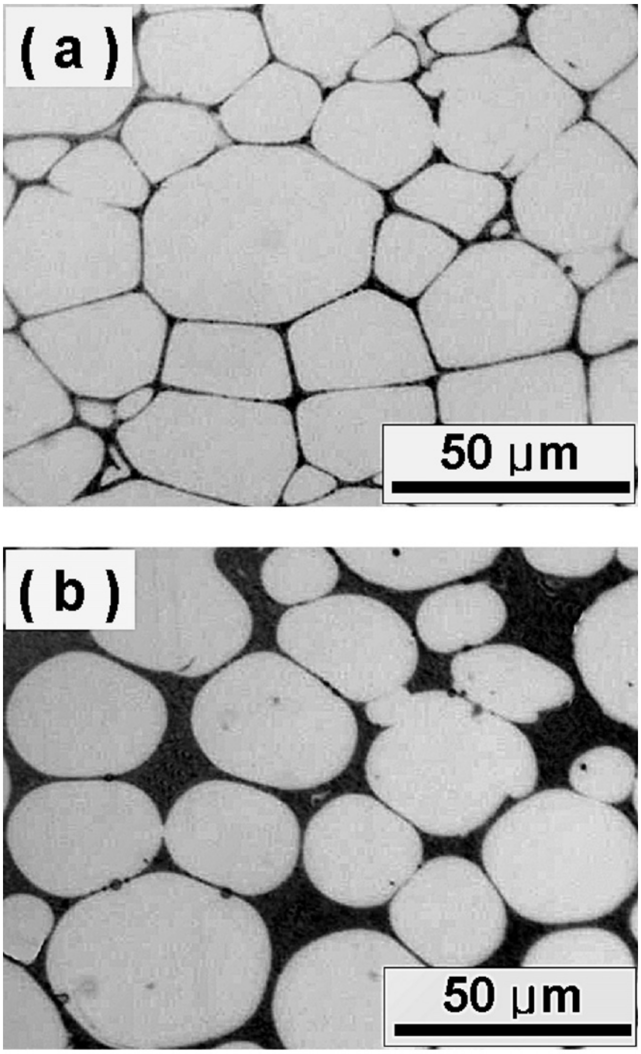

Fig. 1. Optical microstructures observed from the transverse section of (a) Ni/90MG and (b) Ni/70MG after SPS consolidation.

of cracks developed in an MG particle to neighboring MG particles during wear since crystalline Ni is much tougher than a Fe based MG at room temperature. However, such action of Ni is hardly expected in the composite having an MG matrix with Ni particles.

It is interesting to note that the shape of MG particles is polygonal in Ni/90MG and nearly spherical in Ni/70MG. During consolidation in the SLR of the present MG alloy, the MG and surrounding Ni deformed concurrently in Ni/90MG. In contrast, deformation occurs mainly in the soft Ni in Ni/70MG in which the composite sample contains a sufficient large amount of soft Ni.

Fig. 2 shows the result of the wear tests. The applied load was 30 N, corresponding to an applied pressure of 1.53 MPa. The sliding velocity and distance were 0.5 m/s and 1.8 km, respectively. Fig. 2(a) shows the variation of the coefficient of friction (COF) with the increasing volume fraction of MG in the composites. The values of COF of samples Ni/80MG, Ni/90MG, Ni/95MG, and Ni/100MG (monolithic BMG) are between 0.12 and 0.16, which is substantially lower than the values of Cu- and Zr-based BMG alloys reported in reference [4,12]. In order to tackle the low COF value of the present Fe-based BMG alloy, the Vickers hardness test was carried out with a load of 1.961 N. $H_v = 933$ was obtained in the present BMG alloy, which is much higher than Cu- and Zr-based BMG alloys [4]. Accordingly, the low COF of BMG composites containing more than 80% MG is attributed to the extremely high hardness of the present BMG alloy. Composites containing less than 70% MG display an increase in COF with decreasing MG content.

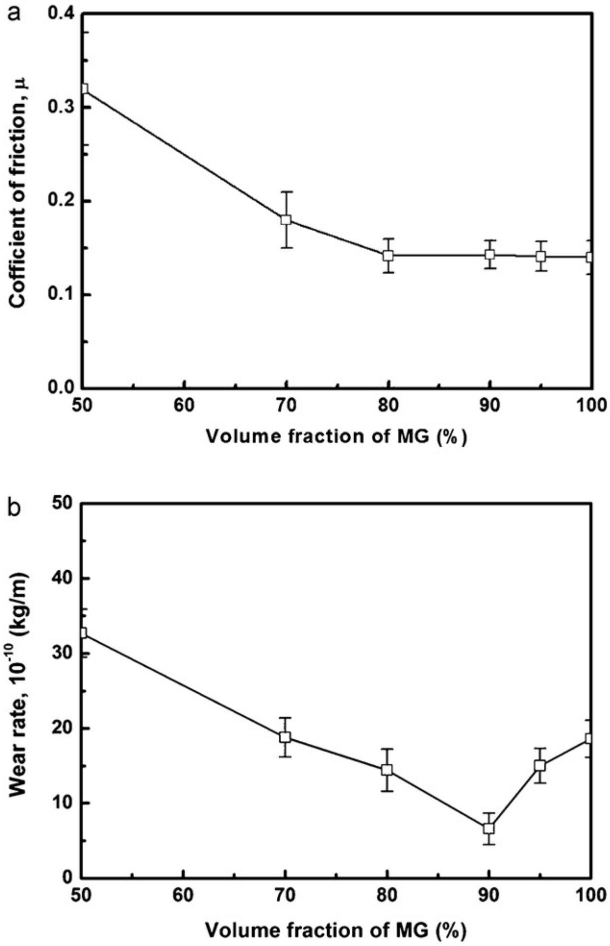

Fig. 2. Variations of (a) coefficient of friction and (b) wear rate of the Ni/MG composites.

Fig. 2(b) shows the variation of the wear rate in various samples. Interestingly, the composite samples Ni/90MG and Ni/95MG exhibited a lower wear rate than the monolithic BMG (Ni/100MG) sample. The sample Ni/90MG displayed a minimum wear rate. The wear rate almost linearly increased with decreasing MG content in the composite samples containing less than 90% MG.

According to the empirical Archard's wear equation [13], sliding wear resistance is roughly proportional to the material's hardness. Indeed, Greer and co-workers reported that the wear resistance for both BMG alloys and conventional hardened crystalline alloys increases with increasing hardness [5]. Because the Vicker's hardness of the present MG particle ($H_v = 933$) was much higher than that of the crystalline Ni matrix ($H_v = 420$), it is expected that the wear loss increased by increasing the volume fraction of soft Ni in the composites. However, a decrease in the wear rate was observed in the composite samples containing less than 10% Ni, as shown in Fig. 2(b).

In order to investigate changes in the wear mechanism of the Ni/MG composites, worn surfaces and wear debris collected were observed by SEM. Fig. 3 shows the worn surfaces of (a) Ni/100MG, (b) Ni/90MG, and (c) Ni/50MG. The worn surface of Ni/100MG (monolithic BMG) shows a smooth plane and areas with severely detached damages larger than 50 μm, which were larger than the size of the original MG particles (15–30 μm) used for consolidation. Ni/90MG also displays a smooth worn surface with a few

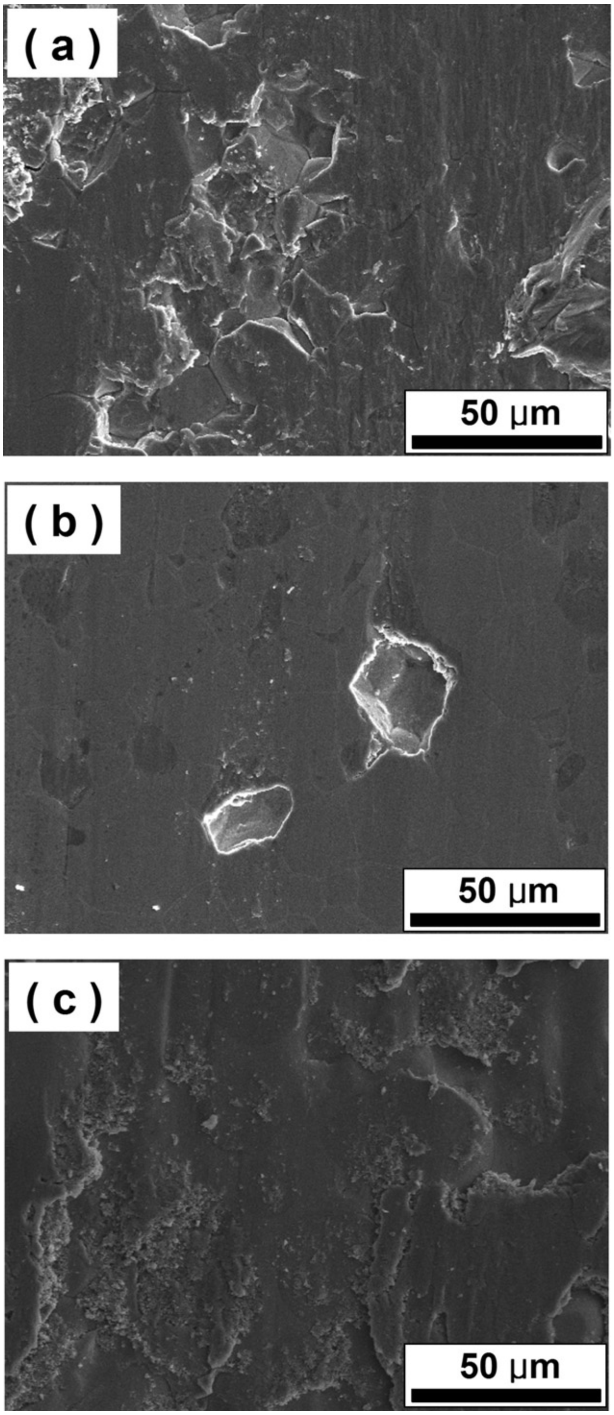

Fig. 3. SEM micrographs of worn surfaces of (a) Ni/100MG, (b) Ni/90MG, and Ni/50MG.

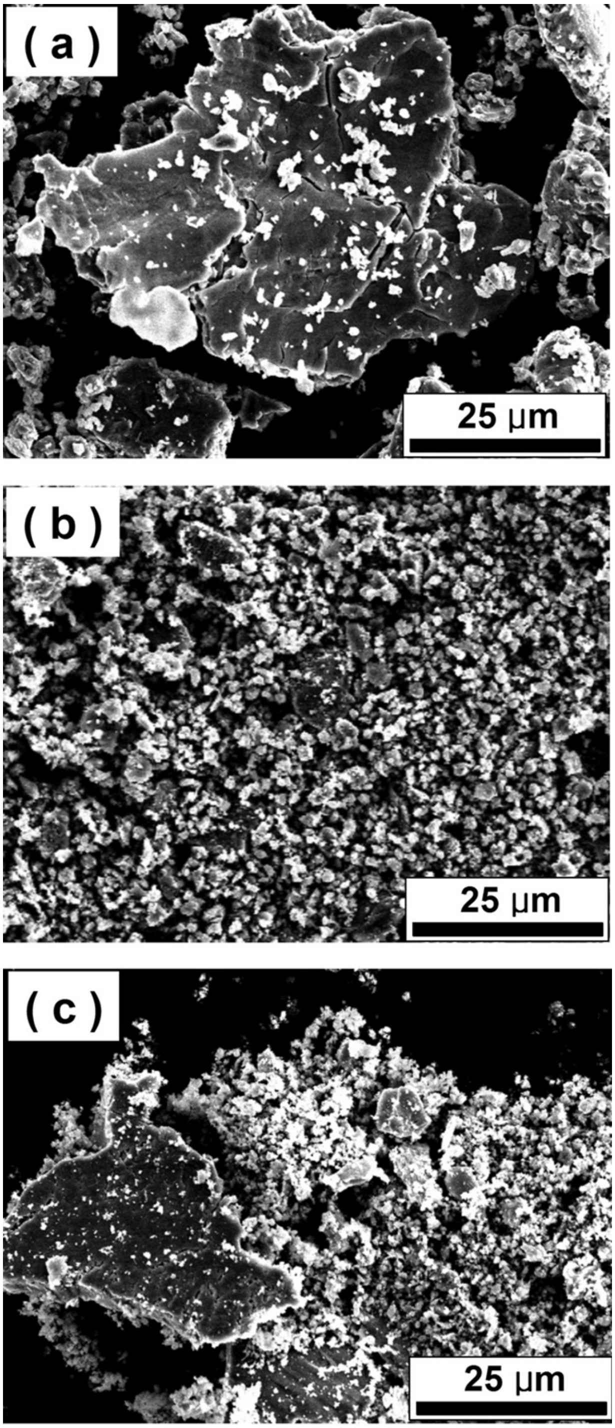

Fig. 4. SEM micrographs of wear debris collected from (a) Ni/100MG, (b) Ni/90MG, and Ni/50MG.

detached damages smaller than 20 μm. Here, detached damages were smaller than original MG particles indicating that damages during wear were limited in an MG particle in the composite. The worn surface of the Ni/50MG composite shows traces of a severe plastic deformation along the sliding direction, which is a commonly observed adhesive wear surface [14].

Fig. 4 shows wear debris collected from (a) Ni/100MG, (b) Ni/90MG, and (c) Ni/50MG. Various sizes of bulky wear debris were observed in Ni/100MG (monolithic BMG). Some large debris display micro-cracks on their surfaces, indicating that the brittle fracture dominated the damage on the worn surface of Ni/100MG. Equiaxed wear debris from Ni/90MG have a fairly uniform size of 2–5 μm, which is much smaller than those from Ni/100MG. Therefore, it is obvious that the damage that occurred in the worn surface of Ni/90MG was much less severe than that of Ni/100MG. In contrast to Ni/100MG and Ni/90MG, the wear debris of the Ni/50MG sample comprise large aggregates and flake-like particles that often develop during the adhesive wear.

In summary, during wear testing, Ni/100MG and Ni/90MG were damaged by a brittle fracture on the worn surface, while Ni/50MG was subjected to adhesive wear. Ni/90MG displayed smaller damaged areas on the worn surface and smaller wear debris than monolithic BMG (Ni/100MG), which is attributed to an increase in the overall toughness of the Ni/90MG composite containing tough crystalline Ni. Composite samples containing a large amount of soft Ni displayed adhesive wear. The adhesive wear rate increases by increasing the amount of soft crystalline Ni.

4. Conclusion

The wear behavior of artificial BMG composites having various fractions of the BMG alloy and crystalline Ni phase was studied. Composite samples containing less than 10 vol.% crystalline Ni displayed higher wear resistance than the monolithic BMG sample, which is attributed to an increase in the overall toughness of the composite containing tough crystalline Ni. The composite samples containing more than 20 vol.% crystalline Ni were damaged by the adhesive wear, which gave rise to an increase in the wear rate by increasing the soft Ni in the composites.

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