Mg-based metallic glass/titanium interpenetrating phase composite with high mechanical performance

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(Received 6 July 2009; accepted 12 October 2009; published online 30 October 2009)

We report an Mg-based metallic glass/titanium interpenetrating phase composite in which constituent phases form a homogeneously interconnected network. The porous titanium constrains shear bands propagation thoroughly and promotes shear bands branching and intersection subsequently. The homogeneous phase distribution promotes regularly distributed local shear deformation and leads to a uniform deformation for the composites. Moreover, the interpenetrating phase structure introduces a mutual-reinforcement between metallic glass and titanium. Therefore, the composite exhibits excellent mechanical performance with compressive fracture strength of 1783 MPa and fracture strain of 31%. © 2009 American Institute of Physics.

doi:10.1063/1.3257699

Mg-based bulk metallic glasses (BMGs) have attracted considerable interest attribute to the high specific strength. However, its application remains a great challenge due to the lack of macro plasticity¹–³ and extremely low performance in large size.⁴,5 As the most brittle one among all BMGs, almost all monolithic Mg-based BMGs have no resistance for shear bands propagation and crack growth.⁶,⁷ Although elastic modulus⁸ and “fragility”⁹ concepts were introduced to design alloy compositions, the Mg-based BMGs did not show remarkable improvement on plasticity as other BMGs.⁸,⁹ Therefore, lots of researches were devoted to improve the plasticity of the Mg-based BMGs by fabricating to BMG composites.¹⁰–¹⁴ It has been reported that where a large volume fraction of ductile phases were introduced into the metallic glassy matrix, significantly improved compressive plasticity¹³ or even tensile plasticity¹⁵ could be obtained for the composites. In contrast to most BMG composites, in which the reinforcement phase are discrete, interpenetrating phase composites¹⁶,¹⁷ have emerged which contain no isolated phases and each individual solid phase within the fully dense composite formed a completely homogeneously interconnected network. This structure creates the opportunity to introduce large-volume of a ductile phase into the metallic glass and leads to a totally uniformed phase distribution. In this letter, we present an Mg-based metallic glass/titanium interpenetrating phase composite, which deforms uniformly under compression and exhibits high fracture strength and large fracture strain.

Porous titanium (purity of 99.9%) was chosen for several reasons. Titanium has good malleability and it is wettable with the Mg-based metallic glass alloy. Moreover, the titanium (ρ=4.5 g/cm³) has similar density with Mg₆₃Cu₁₆.₈Ag₁₁.₂Er₉ BMG (ρ=3.8 g/cm³), so that the composite’s density will not changes significantly even with introduction of large proportions of titanium. The complete details of the porous titanium may be found in Ref. 18. In our research, open-cell porous titanium with a pore size of 30~200 μm and a nominal porosity of 30% was used as the infiltration skeleton. The selected Mg-based BMG was in composition of Mg₆₃Cu₁₆.₈Ag₁₁.₂Er₉. The Mg-based metallic glass/titanium interpenetrating phase composite was fabricated by air pressure assisted infiltration. The subsequent composite is designated as interpenetrating phase composite (IPC).

Mg₆₃Cu₁₆.₈Ag₁₁.₂Er₉ master alloy ingots were prepared by induction melting a mixture of high purity Mg and the prealloyed CuAgEr intermediate alloy in graphite crucibles under a high purity argon atmosphere. The porous titanium skeleton was cut to the size of 5 mm × 70 mm × 200 mm and placed within a thin-wall (0.8 mm) stainless steel crucible and vacuum dried at 200 °C in a tube furnace. After the crucible was evacuated to 3 × 10⁻⁴ Pa, Mg₆₃Cu₁₆.₈Ag₁₁.₂Er₉ alloy was melted at 640 °C for 3 min in a high vacuum sealed crucible, meanwhile, the porous titanium was heated to the same temperature; then high purity argon was applied as the pressure assistant to drive the melting alloy into the interconnected pores of the skeleton and the air pressure was maintained for 2 min to promote complete infiltration. Then the crucible was quenched into a bath of chilled NaCl solution to form the composite. After infiltration, the rod samples were cut from the large-size composite by linear cutting machine and then ground with a diamond abrasive wheel to the desired size. XRD analyzes were performed by a Philips PW1050 m (Cu Kα). Scanning electron microscope (SEM) images were taken with a FEI Quanta 600. High-resolution transmission electron microscopy (HRTEM) image was observed using a FEI Tecnai F30. Quasistatic compression tests were performed in an Instron 5582 universal testing machine at a strain rate of 5×10⁻⁴ s⁻¹ at room temperature. All specimens were prepared to the size of Φ4 mm × 8 mm with both ends of the specimens were parallel to each other. To ensure the results were reproducible, five specimens were tested.

The morphology of the IPC was observed, as shown in Fig. 1(a). On the polished surface of the IPC, titanium spread over the surface and the metallic glassy alloy had completely

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filled all of the large pores and the small pores interconnecting into the titanium mesh wall. The XRD pattern which was taken from the cross-section of IPC exhibits a broad amorphous diffraction pattern superimposed on the titanium crystalline diffraction peaks, as shown in the inset. The interface between the titanium crystalline phase and the glassy phase was observed by HRTEM. As shown in Fig. 1(b), a clear interface between hcp titanium and the glassy phase is marked by an arrow. Several unknown crystalline phases were precipitated along the interface, which suggests interfacial reactions had happened between the titanium and the constituent elements of the metallic glass. The thickness of the reaction layer is estimated about 20–30 nm from Fig. 1(b).

IPC specimens for quasistatic compression test were prepared to a size of \(4 \times 8 \ mm\) in order to test the mechanical properties at a relatively large size. The stress-strain curves of the IPC, \(\text{Mg}_{63}\text{Cu}_{16.8}\text{Ag}_{11.2}\text{Er}_{9}\) monolithic glass and porous titanium are shown in Fig. 2. The porous titanium specimen failed at strength about 800 MPa and strain of 30%. The \(\text{Mg}_{63}\text{Cu}_{16.8}\text{Ag}_{11.2}\text{Er}_{9}\) monolithic glass specimen of \(\varphi 2 \text{ mm} \times 4 \text{ mm}\) was reported to have fracture strength of 1.1 GPa. However, there is a size effect for Mg-based BMGs, in this case the \(\text{Mg}_{63}\text{Cu}_{16.8}\text{Ag}_{11.2}\text{Er}_{9}\) monolithic glass of \(\varphi 4 \text{ mm} \times 8 \text{ mm}\) failed at just under a stress of 825 MPa. By contrast, the IPC exhibited large plastic deformation and a strong increase in strength. The specimen fractured at a stress of 1783 MPa and the overall engineering plastic strain was determined to be about 31 ± 1.5%. The dash line in Fig. 2 shows the true-stress-true strain of the IPC; a clear increase of the flow stress representing the “work-hardening” behavior had occurred after yielding. The fracture true stress and true strain determined by the true stress-true strain curve are 1271 MPa and 40%, respectively.

In order to clarify the deformation process and shear bands propagation, four IPC samples were compressed to the preset engineering strain \((\varepsilon _{E})\) of 4%, 14%, 24%, and 31% and designated as A, B, C, and D, respectively. The macroscopic appearances of them are shown on the inset of Fig. 2. The specimens lost their cylinder shape gradually with the increasing of strain.

The profiles of the IPC compression test specimen A, B, C, and D were investigated by SEM. At a strain of 4%, several shear bands had been activated in the metallic glassy phase of specimen A, as shown in Fig. 3(a). Most of them were initiated from the metallic glassy-titanium interfaces and almost vertical to the compressive direction. The inset shows an enlarged view of those shear bands. Those shear bands were parallel with each other and almost no intersection occurred. When increased the strain to 14%, as shown in Fig. 3(b), multiple shear bands had formed uniformly in the metallic glass of specimen B. Besides the shear bands generated in advance (black arrows) which were vertical with the compressive direction, newly formed shear bands (white arrows) which laid at 45° from the compressive direction could be observed. The inset shows the main shear bands had switched direction due to the intersection of shear bands. No matter what direction had switched to, shear bands propagation was under the constraint of titanium. It implies the constraint of titanium and intersection of shear bands could effectively prevent the shear band runaway, which is devastating for monolithic Mg-based BMGs. When the strain reached 24%, abundant shear bands were homogeneously
generated in the metallic glassy phase of specimen C, as shown in Fig. 3(c). The inset shows shear bands which were vertical to the compressive direction (black arrows) adjusted its direction when they got close to the main shear band (white arrows) until they align themselves in the direction of main shear band. It implies most shear bands were forced to orientate to the shear direction when strain reached 24%. The main shear band cut through the titanium and slip bands of titanium could be clearly observed on the encountering area. The appearance of microcrack implies the porous titanium began to lose its ability of shear band constraint. When the strain reached 31%, just before the final fracture, the profile of sample D exhibited a much more severe deformation of both metallic glass and titanium, as shown in Fig. 3(d). A long crack about 45° to the compression direction implies that the IPC could no longer sustain the increasing stress after the engineering strain reaches 31%. Besides the long crack, a series of short cracks (black arrows) which laid at about 45° to the compression direction and parallel or vertical to each other could be clearly observed. The inset shows two parallel short cracks. Both of them were initiated in the titanium then cut through the glassy phase and cut into the titanium on the other side. The appearance of abundant regularly distributed short cracks implies the macroshear deformation of IPC was homogeneously decentralized to the local shear deformations of titanium and metallic glass then led to a uniform macro deformation.

As shown on Fig. 3, shear bands were homogeneously generated in the metallic glass on every stage of compressive deformation. Each encircled glassy phase seems deforming individually. As a matter of fact, the interpenetrating phase structure connects all enclosed glassy phase entirely. If all the porous titanium was removed from the IPC, the remained metallic glass would form a self-supporting, open-celled foam. During compressive deformation, the two constituent foams deformed coordinately under the constraint of each other. Shear band propagation in the metallic glass was totally confined by the titanium; branching and intersection of shear band was promoted. It prevented the shear bands runaway and led to the increase of flow stress of metallic glass. Meanwhile, the slip deformation of titanium was also under the constraint of metallic glass. The “soft” titanium was work-hardened simultaneously in order to keep constraining the shear bands propagation. It led to further enhancement of compressive strength. The mutual-reinforcement of titanium and metallic glass endows the IPC with fracture strength of 1783 MPa and fracture strain of 31%. Moreover, both the long crack and short cracks prefer to cut through the titanium or metallic glass, rather than propagate along the interfaces, which is dominate for several fiber reinforced BMG composites. It implies the interfacial layer might have positive contribution to the high mechanical performance of IPC.

In summary, the Mg-based metallic glass/titanium interpenetrating phase composite was successfully fabricated. Due to the interpenetrating phase structure, shear bands propagation was constrained thoroughly. The interpenetrating phase structure promotes homogeneously distributed local shear deformations of titanium and metallic glass to decentralize the deformation of IPC. Moreover, the interpenetrating phase structure introduces a mutual-reinforcement between metallic glassy and titanium and leads to the excellent mechanical performance; especially they were tested with relatively large-sized specimens. Our research indicates that fabricating brittle BMGs into interpenetrating phase composites with ductile metals can be an effective method to enhance mechanical performance of brittle BMGs.

The authors gratefully acknowledge the financial support from the Ministry of Science and Technology of China (Grant No. 2006 CB605201) and the National Natural Science Foundation of China (Grant Nos. 50825402 and 50731005).