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Fracture behavior of bulk metallic glass/metal laminate composites

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Abstract

The fracture behaviors of laminated composites of bulk metallic glass (BMG (Vitreloy 1))/crystalline layer have been examined. The composites stacked by BMG/thin Zr layer (25 μm) have been bonded by electron-discharge bonding technique. The fracture tests have been carried out by non-standard self-designed subsize-charpy tester. When the number of BMG layer increases up to three layers, the fracture energy for the laminated specimen is increased due to crack redirection and absorption of the fracture energy at the crystalline layer during fracture.

Keywords: Composite materials; Bulk metallic glasses; Fracture energy

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1. Introduction

A fabrication of large-size bulk metallic glasses (BMGs) with a relatively slow cooling rate as low as 1 K/s has received an attention due to their unique properties such as high strength and high corrosion resistance [1,2]. However, the catastrophic fracture behavior of metallic glasses upon applied loading has led a fabrication of in situ and/or ex situ composites, exhibiting a large potential for an enhancement of fracture toughness [3]. Alternatively, a novel composite fabrication process has been explored by adopting laminated architecture, which can maximize uni-directional toughness [4–6]. Especially, Al-based composite alloys have exhibited a significant enhancement of fracture toughness via fabrication of laminated structure alternating hard/soft materials, in which the toughening enhancement can be achieved due to the formation of alternating layered architecture [4]. Furthermore, the investigation of laminated composites can provide useful scientific information for materials fracture behavior [7–9]. Numerous attempts of novel architectural design in order to provide an enhancement of toughness for Al composites or ceramics have been explored [4,10–12]. One model approach of laminated composites fabricated by soldering of a sandwich design with one amorphous ribbon and crystalline layered specimen focused ribbon fracture behavior and showed a potential for enhancement of crack resistance [13]. However, a detailed investigation of novel architectural design for BMG/metal laminated composites has not been reported.

In the present study, a special attention has been given to the fracture behavior of laminated BMG/metal composites bonded by electro-discharge technique for the first time. The fracture behavior and fracture energy have been investigated by means of self-designed subsize-charpy tester. The estimated fracture energy for laminated BMG composites showed an enhancement of the fracture energy. The fracture behavior of laminated composites is presented together with an underlying mechanism for enhancement of fracture energy.

2. Experimental

Thirty grams ingots with a nominal composition of monolithic Vitreloy 1 ($Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (at.%)) have been made by arc-melting elemental components and Be–Cu–Ni alloys in a Ti-gettered Ar atmosphere. In order to fabricate a plate-shape BMG a self-designed plate-shaping equipment was used: after melting of the ingot by arc in an Ar atmosphere, the melt was sandwiched immediately between two cupper rods.

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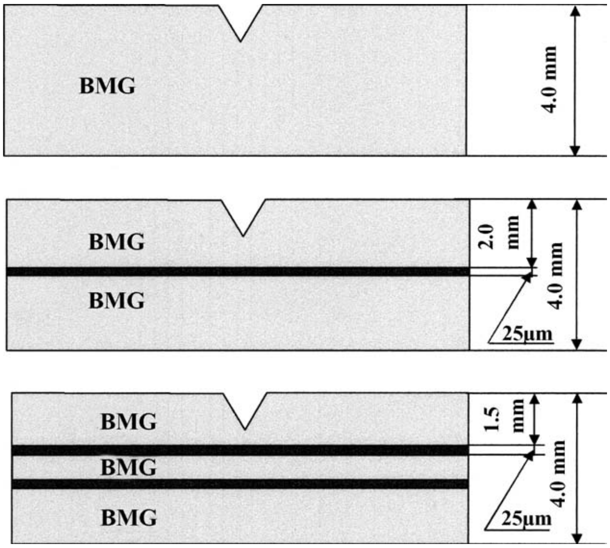

Fig. 1. Schematic figures of prepared specimen dimensions.

For the preparation of bonding process, the BMG plate was cut into a rectangular shape.

A thin Zr metallic foil (25 µm) was purchased from Alfa Aesar. The metallic layer was selected upon similarity of the constituent of Vitreloy 1. In order to fabricate laminated composites, the thin foil was inserted between two and three pieces of the BMG. In order to minimize a variable of the sample roughness during bonding process, all of the BMG surface was polished with a 0.1 µm (Al_2O_3 powder) on a cloth. The capacitor of the charge electron equipment was used with a constant value of 450 µF and the maximum input energy for sample bonding was about 17 kJ. Following the bonding process, the specimen was cut as a dimension of 3 mm × 4 mm × 15 mm (width, height and length) by electro-discharge machining. The thicknesses of each BMG piece were reduced for the two- and three-layered laminated composite, but all of the final specimen dimension was maintained as an equivalent size. The schematic specimen dimension and shape are shown in Fig. 1. For the three-layered composite, in order to minimize the dimensional effect during machining, the thickness of both the top and bottom layer were set as 1.5 mm, and the middle layer was set as 1.0 mm. The total layer thickness of all of the specimen has been set as 4 mm. In order to measure the fracture energy of the specimen, a self-designed subsize-charpy tester was used and the fracture energy was measured. Briefly, the designed subsize-charpy tester is equipped with a free drop anvil and oscilloscope that can receive signals during specimen fracture. The signals have been received from a load cell composed of strain gage attached on the striking anvil. The detailed equipment information and data reliability have been reported elsewhere [14]. Following the fracture tests, the microstructures and fractured surface were investigated by Optical Microscope and SEM (Scanning Electron Microscope, Hitachi S-2700).

3. Results

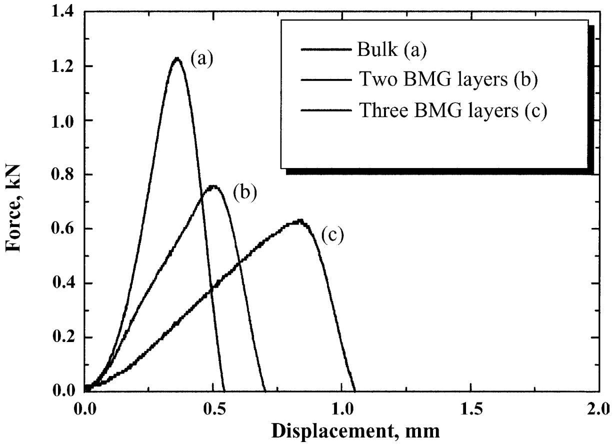

Fig. 2. Fracture test results for (a) monolithic, (b) two, and (c) three BMG composites.

Fig. 2 shows the fracture energy corresponding to the BMG layer numbers. Fracture energy (E) was estimated from an integration value of applied force (F) upon displacements (t) ($\int_0^t \text{force}\, dt$). The fracture energy was obtained by dividing the specimen cross-section area affected by the size factor [15]. When the number of BMG layer was increased, the fracture energy was enhanced. It should be noted that the maximum force for fracture energy of the BMG was highest for the monolithic BMG, while the laminated BMG showed lower values upon increasing layer numbers. However, the total fracture energy was increased for the three-layered BMGs. The measured maximum forces and corresponding fracture energy (E_i: fracture energy up to maximum force; E_T: total fracture energy) are shown in Table 1. The fracture energy of three-layered BMG composite was increased by about 40%, while the maximum fracture force was lowered, compared with the monolithic BMG specimen.

Fig. 3(a) shows the surface of the monolithic BMG fractured sample. The main crack developed in an irregular manner. Also, small cracks were observed along the main crack direction (marked as A), implying that such small cracks and shear bands contribute to dissipate fracture energy. Fig. 3(b) displays the surface of two-layer BMG specimen. Again, cracks developed in an irregular manner. It is specially noted that the cracks redirect when the crack reaches an interface and small cracks developed at the interface area (marked as B). Fig. 3(c) shows the surface of three-layer BMG specimen. It is clear that a fair amount of small cracks and shear bands were developed at the interface compared with other specimens (marked as C). Also, the cracks were redirected at the interface. It should be mentioned that the cracks and shear bands were observed all of the internal interface area. At the same time, the shear bands were also developed at the place that the anvil hits the specimen (marked D).

Table 1
Fracture force and energy for bulk, two- and three-layered BMG specimen (E_i: the energy that the materials absorbed until fracture until maximum force, E_T: total energy for complete fracture, F_{max}: maximum force for sample fracture)

Sample	F_{max} (kN)	E_i (J)	E_T (kJ/m^2)
Bulk	1.23	0.18	19
Two-layer	0.77	0.19	22
Three-layer	0.63	0.26	27

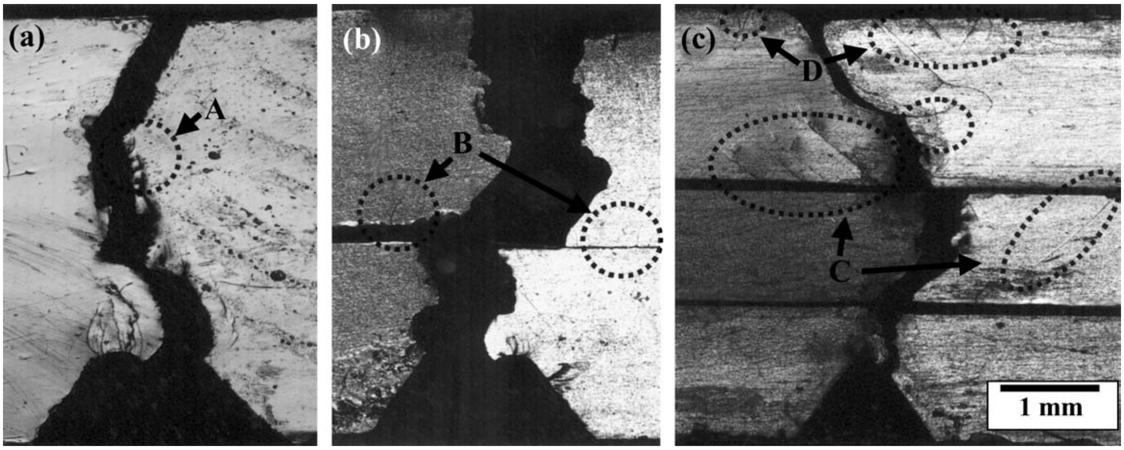

Fig. 3. Specimen outlook following fracture tests for (a) monolithic, (b) two, and (c) three BMG composites.

Fig. 4 shows SEM of (a) monolithic (b) two-layered, and (c) three-layered BMG cross-sections following fracture. The fractured surfaces of the entire specimen show a typical vein pattern. The morphology of vein patterns placed near the notch area is shown in Fig. 4(d) and the morphology of them located away from the notch area is shown in Fig. 4(e). It is probable that the morphology of the fracture surface is closely related to the stress mode. Further work is being focused on the morphology of the vein pattern.

4. Discussion

A noble specimen architecture in a form of laminated composite has been attempted in several approaches in order to enhance fracture toughness and fracture energy in Al-based composite systems or ceramics [4,5]. The laminated composite is fabricated by alternating ductile and hard materials. The achievement of high toughness is due to the incorporated ductile phase, while there is a loss of materials strength due to the presence of a ductile phase [4]. It has been reported that crack redirection and fiber pulling force are mainly responsible for the enhancement of high toughness of the laminated composites for ductile phase reinforced composites [16]. The fracture behavior of monolithic BMGs exhibits a different mode from conventional alloys. They usually undergo a catastrophic fracture upon applied loading. However, for a ductile/hard phase reinforced BMG composites, a fair number of shear bands are usually observed, implying that the formation of shear bands may provide a beneficial effect for a load transfer [3]. During fracture of BMGs, the formation of shear bands provides nucleation sites for a load transfer. For example, for the cases of the BMG based composites, the observations of a large number of shear bands exhibited a large amount of plasticity after compression tests, while the catastrophic fracture of BMG is a normal phenomenon for monolithic BMGs [17]. In this regard, the observations of small cracks and shear bands developed at

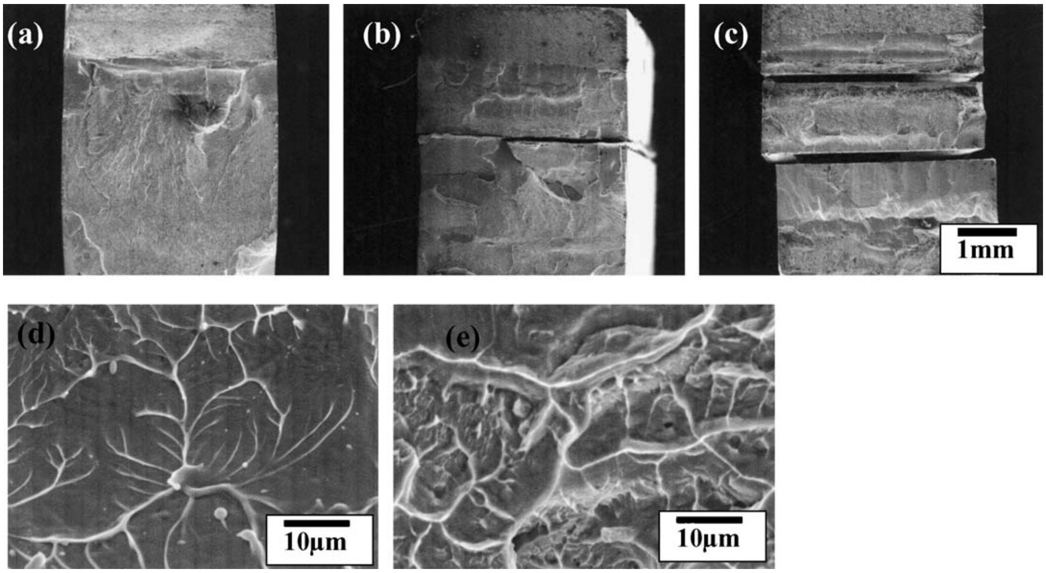

Fig. 4. Cross-sections of specimen following fracture tests for (a) monolithic, (b) two, and (c) three BMG composites, (d) and (e) are enlargements of fracture surfaces.

the interface indicate that the energy may dissipate at the interface and the direction of main crack is changed as shown in Fig. 3(c), implying that the crack redirection and the formation of the shear bands are an evidence for the enhancement of fracture energy of the laminated composites. It has been reported that further increase of laminated layer affects fracture toughness [7]. When the laminated Al layer was increased up to 10 layers, the impact energy of the laminated composites has been increased by about two times [7]. However, for the present situation there was a difficulty in measuring fracture toughness due to limited sample dimension.

It has been shown that the fracture energy for charpy tests appears useful data for estimation of fracture energy of materials [7,14]. The integration value of the fracture graph (Fig. 3) directly indicates fractured energy of specimen. Especially, the fracture energy up to maximum fracture force is significantly important for estimation of material fracture energy, since after maximum force the trajectory of the graph in Fig. 3 indicates a force for the anvil penetration after fracture. Since part of the graph after fracture (after maximum force) may include complex factors such as anvil shape, we have omitted the anvil penetration force. The fracture energy value is shown in Table 1. For the laminated BMGs when the BMG layers are increased up to three layers, the fracture force was lowered from 1.25 to 0.6 kN. However, it is evident that the total integration values of three layers increased from 0.18 to 0.26 kJ, which is increased by about 40% of the energy. During this estimation, the deformation energy has been omitted upon the brittle nature of the selected BMGs [18]. The enhancement of fractured energy indicates that the specimen has higher fracture resistance due to the specimen design. The observations of the fractured surface indicate that the propagation of cracks is accompanied with shear bands formation. When the main crack passes through a thin crystalline layer, it appears that the shear bands are formed along the interface, which may serve as a site for energy dissipation during fracture of BMG. It is noted that the fracture energy for two-layer BMG was not clearly increased compared to the monolithic BMG, implying that when the stacking number of BMGs are low (i.e., for two layers), the enhancement of fracture energy is negligible, corresponding to the previous report in the Al laminated composite [7]. For the three-layer BMGs, it is clear that the shear bands (or small cracks) are developed at the interface and the top (where an anvil hits) of the specimen as well, indicating that the formation of shear bands is an indirect proof for load distribution. It appears that the laminated specimen using a novel architectural design shows a useful application for enhancement of fracture resistance.

5. Summary

The fracture behaviors of laminated composites of BMG (Vitreloy 1)/crystalline layer have been examined. The fracture tests have been carried out by non-standard self-designed subsize-charpy tester. When the number of BMG layer increases up to three layers, the fracture energy of the laminated specimen is increased by about 40%. It appears that the enhancement of the fracture energy for the laminated composite is mainly attributed to crack redirection and absorption of the fracture energy at the crystalline layer during fracture.

Acknowledgement

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