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Tuning plasticity of in-situ dendrite metallic glass composites via the dendrite-volume-fraction-dependent shear banding

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ABSTRACT

This work performs a systematic investigation of identifying how the volume fraction of the in-situ dendrites affects the plasticity of metallic glass composites. The quasi-static uniaxial compressions show that the global plastic strain does not follows a linear rule-of-mixture with the dendrite volume faction, instead, a slow-fast-slow enhancement behaviour is observed with increasing dendrite volume fraction. It is demonstrated that the nucleation and propagation of shear bands in these composites are dependent on the dendrite volume fraction. When the dendrite volume fraction exceeds a critical value, multiple shear bands emerge in a spherical plastic zone around a dendrite. It is further proposed that the percolation of these spherical plastic zones contributes to the fast increase in the plastic strain of the glass composites. Our findings offer important implications for the microstructural optimization of the metallic glass composites with desirable mechanical properties.

1. Introduction

Bulk metallic glasses (BMGs) have attracted extensive interests due to their remarkable properties, such as high strength, extraordinary hardness, and excellent wear resistance [1–5]. However, at room temperature, BMGs usually undergo the plastic flow localization into nanoscale shear bands [6–9]. Uncontrolled shear banding can incur catastrophic failure with very limit ductility [6,10], impeding wide applications of BMGs as structural materials. An effective way to solve this bottle-neck problem is to develop BMG composites by in-situ introducing crystalline second phases [11–21]. It is expected that these crystalline phases facilitate shear band nucleation at their interfaces with the glass matrix, and meanwhile act as obstacles to shear band propagation into cracks due to their relatively high shear-band toughness [22,23]. However, the presence of crystalline phases tends to decrease the global strength of composites as compared to pure matrix glasses. Therefore, sustained efforts have been made to optimize the strength and plasticity of composites by modifying the sizes, spacing, shape, distribution and volume fraction of crystalline phases [13,24–31]. Among these, the volume fraction is a structural parameter to effectively tune the composite's properties. It was found that, the plastic deformation exhibits a nonlinear enhancement as the volume fraction of crystalline phases increases above a critical value [13,27,32]. Lee et al. [13] and Liu et al. [32] have ascribed this phenomenon to percolation of shear banding, corresponding to a specific configuration of crystalline phases' distribution. However, the picture of how shear banding evolves in composites with increasing volume fraction of crystalline phase remains unclear up to now, and the relationship between the percolation point of global plasticity and the spatial configuration of crystalline phases also deserves further investigation. In this study, Zr-based BMGCs containing different volume fractions of dendrites were synthesized. We then investigate how the dendrite volume fraction affects shear banding behaviours and the plasticity, using interrupted compression technique and microscopic image analysis. A percolation transition, i.e., a brittle-to-plastic transition, was found with increasing dendrite volume fraction. The shear banding behaviours were revealed below and above the percolation threshold.

2. Materials and methods

According to the pseudo-ternary phase diagram with apexes of Zr, Ti+Nb, and $Be_9Cu_5Ni_4$ [33], as shown in Fig. 1, six alloys were designed along the line of $(Zr_{75}Ti_{15}Nb_{10})_{100-y}(Be_{50}Cu_{27.5}Ni_{22.5})_y$ with y=20, 26, 27, 29, 30 and 32. It was shown that Be, Cu, and Ni are distributed preferentially in the glass matrix, and the composites with different volume fractions of the dendrites can be obtained via changing the value, 'y' [33]. The master ingots of the six composites were prepared by melting the mixture of high-purity Zr, Ti, Nb, Cu, Ni, and Be elements (> 99.9 wt%) under a Ti-gettered argon atmosphere. Afterwards, the ingots were crushed into pieces and remelted by

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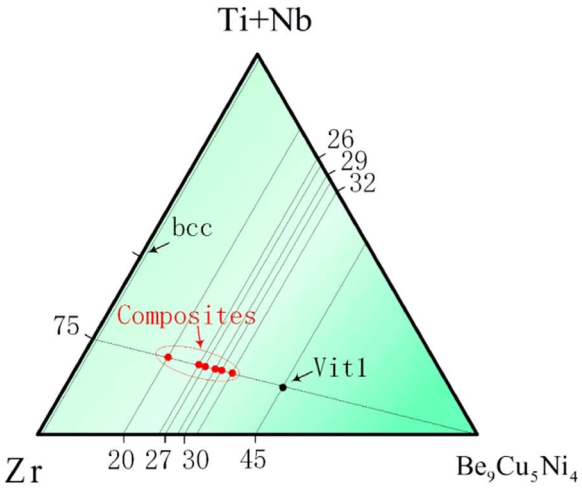

Fig. 1. Pseudo-ternary phase diagram with apexes of Zr, (Ti+Nb), and $Be_9Cu_5Ni_4$. Compositions of the fabricated composites (red spots) and a typical monolithic metallic glass Vit 1 (black spot) are marked. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

induction under a high pure argon atmosphere, and subsequently, cast into a copper mould with a 10-mm-diameter cavity. The phases of the samples were examined by X-ray diffraction (XRD) in a Philips PW1050 diffractometer using Cu Kα radiation. Rectangular bar specimens (7×3.5×3.5 mm) for mechanical tests were taken from the central area of the cylinders by electric spark machining. Compression tests were conducted using a MTS 810 mechanical testing machine under a strain rate of 5×10^{-4} s^{-1} at room temperature. The microstructures of the as-cast samples, the lateral surfaces and fracture surfaces of the deformed samples were investigated by scanning electron microscopy (SEM) with an energy dispersive X-ray spectrometer (EDS). Before the SEM observations, the lateral surfaces of the unreformed samples were mechanically polished by using the 1-μm-diamond paste. The microstructures of the composites before and after compressions were observed by transmission electron microscopy (TEM) in a JEM-2100F instrument. The TEM samples were prepared by mechanically grinding, followed by ion beam thinning using a Gatan duo-ion mill equipped with a liquid-nitrogen-cooled stage.

3. Results

3.1. Material characterization

Fig. 2a shows the XRD patterns of the as-cast 10-mm-diameter rods of the six alloys. It can be seen that intense crystalline peaks, marked as different crystalline planes of the body-centred cubic (b.c.c) solid solution, are superimposed on a broad diffuse scattering maximum of the amorphous matrix. This demonstrates that all the six alloys have a two-phase microstructure. It is noted that by decreasing the portion of $Be_{50}Cu_{27.5}Ni_{22.5}$ in the composition, the intense crystalline peaks increase remarkably, but the broad diffraction peak becomes less obvious. Fig. 2b shows a TEM image of one typical alloy with the composition $(Zr_{75}Ti_{15}Nb_{10})_{100-y}(Be_{50}Cu_{27.5}Ni_{22.5})_y$ (y=29), with light and dark areas corresponding to the dendrites and the glass matrix, respectively. The high-resolution TEM (HRTEM) image in Fig. 2c, taken from the rectangle in Fig. 2b, exhibits the clear and tight interface between the two phases. The selected area electron diffraction patterns (SAED) in the insets of Fig. 2c show the typical glass matrix and the b.c.c crystalline dendrites, respectively, confirming the dual-phase structure of the composites.

Fig. 3 presents the characteristic microstructures of the six composites observed by the SEM backscattered electron mode, exhibiting the tendency of the dendrite volume fraction f_d increasing with the decreased value of y, which is consistent with the XRD results. By analysis of greyscale values of SEM images, f_d is determined for each alloy. It has been revealed that crystals grouped closely are actually have the same orientation and form a single dendrite [31] . For the alloy with an 8% dendrite volume fraction, the individual dendrite size is about 20 μm, and the dendrites are sparsely distributed among the glass matrix. As y decreases to 20, corresponding to the value of f_d 55%, the dendrites are nearly touched each other, while the dendrite size remains the same. The microstructure characters of the composites, such as the volume fraction, dendrite size, dendrite arm diameter as well as the composition of the dendrites, are summarized in Table 1.

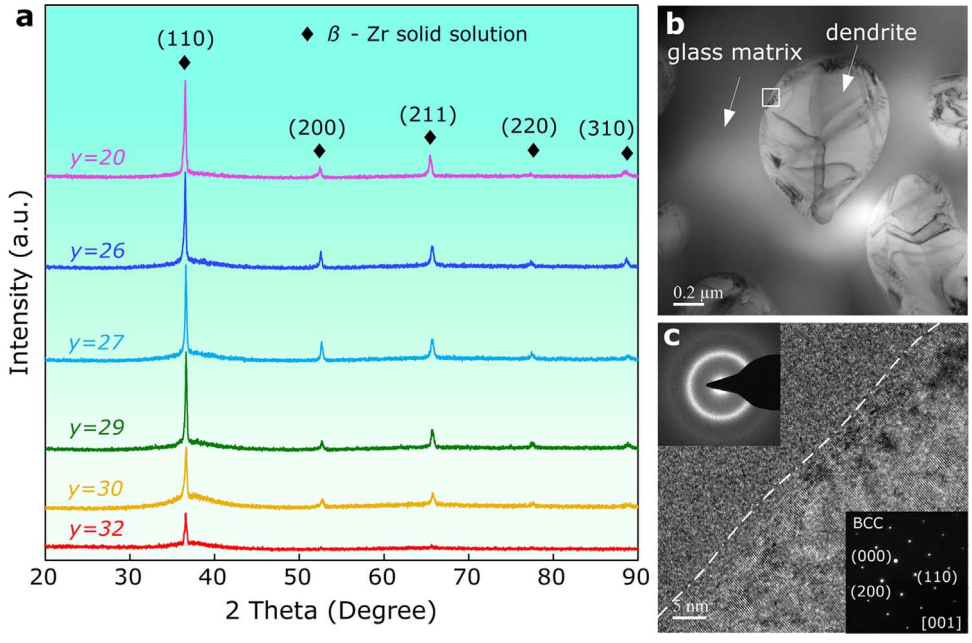

Fig. 2. (a) XRD patterns of the as-cast 10 mm diameter cylinders of the composites $(Zr_{75}Ti_{15}Nb_{10})_{100-y}(Be_{50}Cu_{27.5}Ni_{22.5})_y$ with different value, y. The TEM image (b) of the composite with y=29 at low magnification and its HRTEM image (c) of the interface taken from the rectangle in (b). Insets in (c) on the upper left corner and the bottom right corner are the SAED patterns corresponding to the glass matrix and the dendrites, respectively.