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Shear band formation and mechanical properties of $Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ bulk metallic glass/porous tungsten phase composite by hydrostatic extrusion

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ABSTRACT

$Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ bulk metallic glass/porous tungsten phase composites were prepared via a method by combining infiltrating the molten alloy into the reinforcement with hydrostatic extrusion. The deformation and failure behavior of the as-extruded composite were investigated at room temperature under quasistatic compression. Compared to the as-cast composite, the as-extruded composite presented greater flow stress and lower fracture strain. Different from the fracture mode of multiple macro shear bands for the as-cast composite, fractrographic analysis revealed that the specimen for the as-extruded composite fractured by a mixture of shearing and axial splitting. It is suggested that the increase in flow stress for the as-extruded composite is attributed to the extrusion process which introduced hardened condition in the tungsten phase. The fracture strain of the as-extruded composite decreased by comparison with the as-cast composite is proposed to result from the joint effects of the employed extrusion process sacrificed part of the plasticity, relatively high flow stress exceeded the fracture stress of the pure metallic glass, and the elongated grain structure resulted in splitting mode for the as-extruded composite.

1. Introduction

Bulk metallic glasses (BMGs) have been regarded as a potential structural material since their first emergence about 40 years ago. This class of materials has many promising properties, e.g. extremely high strength and hardness, large elastic strain limit combined with relatively high fracture toughness, as well as good wear and corrosion resistance [1–5]. However, the work hardening and toughness of BMGs are badly limited by the catastrophic shear band propagation because of the absence of dislocation and grain boundary structures [6–9]. The attempt to improve the ductility of BMGs leads to the development of BMG based composites, such as composites reinforced with refractory metals or metal fibers, ceramic particles or carbon nano-tubes, *in situ* formed ductile dendritic phase or *in situ* formed nanocrystals, etc. [10–16]. In the BMG based composites, the reinforced phases are expected to hinder the propagation of the single shear band within BMGs and seed the initiation of multiple shear bands throughout the specimen [16–20].

Usually, the mechanical properties of materials can be improved by varying the element compositions, preparing composites or employing thermo-mechanical workings (such as swaging, extrusion, and aging). Although considerable research efforts for improving the plasticity of BMGs have been preformed by optimizing the element composition and developing composites, limited effort has been focused on that improving the properties of BMGs or BMG based composites by thermo-mechanical processing. Yokoyama et al. [21] first performed a cold rolling treatment on $Zr_{55}Cu_{30}Al_{10}Ni_5$ BMG to improve the ductility of the alloy, demonstrated that the cold rolling process was valuable. Hydrostatic extrusion, as a general deformation technology, could achieve a deformation amount as high as 60–80% in section area reduction by a single extrusion operation, which has been demonstrated to be one of the most effective processes for deformation processing of difficult-to-deform materials [22–25]. Recently, Xue et al. [26] reported a new Zr-based metallic glass/porous tungsten phase composite deformed by hydrostatic extrusion, which exhibited improved strength in comparison to the as-cast composite. However, so far there are limited data to reveal the failure behavior and mechanism of the as-extruded composite under quasistatic compression.

In the present study, hydrostatic extrusion of a $Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ BMG/porous tungsten phase composite was performed. The effects of hydrostatic extrusion on microstructures, mechanical properties, and deformation behav-

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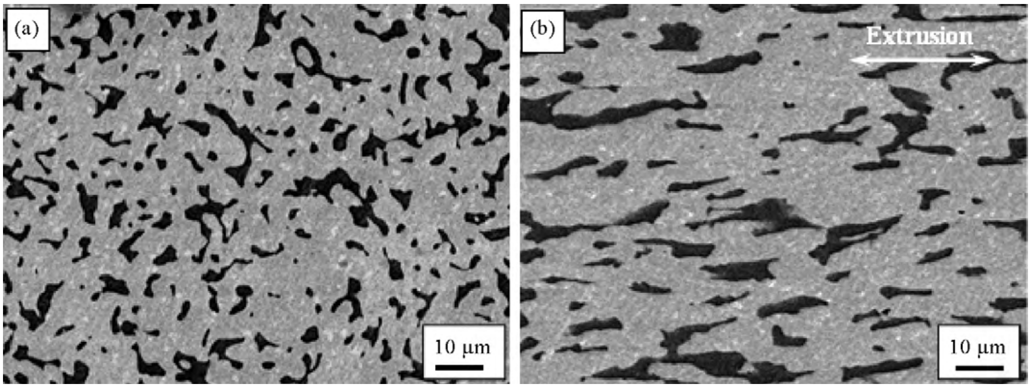

Fig. 1. Micrographs of the as-extruded composite: (a) transverse section and (b) longitudinal section.

iors of the present composite under quasistatic compression were investigated and discussed in detail.

2. Experimental procedures

Ingots of the $Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ alloy were prepared by alloying together the element metals with purity of 99.8% or higher in an arc-melting furnace under Ti-gettered Argon atmosphere. The porous tungsten with 80 vol.% tungsten was made by power metallurgy, which is noted that the porous tungsten exhibits a three-dimensional (3D) net structure. The $Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ BMG/porous tungsten phase composite was prepared by pressure infiltration. The as-cast composite rods were then hydrostatically extruded at 663 K with section area reduction of 53.8%, no further processing was carried out. A detailed description of preparing the as-extruded composite can be found elsewhere [26].

The microstructure of the as-extruded composite is shown in Fig. 1. The plane perpendicular to the extruded direction in Fig. 1(a) exhibits that the dark metallic glass phase is surrounded by the grey tungsten phase. However, the longitudinal plane in Fig. 1(b) shows a strongly elongated structure in the direction of the extrusion. The X-ray diffraction patterns of the as-extruded composite were given by Xue et al. [26], which demonstrated that no other phases were detected within the sensitivity limit of X-ray diffraction. A wire electro-discharge machine (WEDM) was used to cut cylindrical specimens 2.5 mm in diameter and 5 mm in length from the composite rods. The as-extruded specimen was machined with the longitudinal axis parallel to the extruding direction. Quasistatic compression tests were performed on a CMT 4305 testing machine with strain rate of $1.7 \times 10^{-3}\,s^{-1}$ at room temperature. To evaluate the evolution of the surface morphology of the specimens with increasing strain level, the lateral surfaces of the specimens parallel to the axial direction were polished before compression.

3. Experimental results

Fig. 2 shows the typical true stress–true strain curves for the pure metallic glass, the as-cast composite, and the as-extruded composite with strain rate of $1.7 \times 10^{-3}\,s^{-1}$ at room temperature. The stress–strain curve of the as-cast composite shows a change in slope (a “dogleg”) during the elastic deformation stage and a large fracture strain of up to be 80%, the “dogleg” indicates that the tungsten phase yielded first due to its lower yield strength than that of the metallic glass phase. The flow stress sustained by the as-extruded composite increased by at least 15% in comparison with that of the as-cast composite during the same loading case, but the fracture strain of the as-extruded composite decreased to be 50%. It is noted that the fracture strain of 50% for the as-extruded composite is still much greater than those of all the previous tungsten reinforced metallic glass matrix composites [27,28]. The as-cast composite showed very strong work hardening behavior up to strains on the order of 40%, subsequently exhibiting nearly perfect plasticity with no obvious fluctuating of flow stress as the strain increased further; however, the as-extruded composite exhibited work hardening behavior until failure.

We cut the post-deformed specimens along the loading direction, polished one of the sectioned surfaces, and examined it with SEM. Fig. 3 shows the micromorphologies of both the post-deformed specimens for the as-cast and the as-extruded composite under quasistatic compression. Comparing Fig. 3(a) with Fig. 3(b), it is seen that the width of shear band in specimen for the as-cast composite in Fig. 3(b) is greater than that of the specimen for the as-extruded composite in Fig. 3(a). There existed numerous fragmented tungsten phase within the shear band of the as-cast composite in Fig. 3(b), however, nearly nothing existed within the shear band of the as-extruded composite during quasistatic loading case in Fig. 3(a).

Fig. 4 shows the side SEM faces of the specimens both for the as-cast composite and the as-extruded composite at different degree of deformation. It is seen in Fig. 4(a) that microcracks mainly appeared in the tungsten phase during the early stage of deformation, with the increasing strain level as seen in Fig. 4(c and e), more and more microcracks formed in the tungsten phase and substantive shear bands were initiated in the metallic glass phase, the same phenomenon was also observed in the as-extruded composite in Fig. 4(b, d, and f). Compared to the surface morphology of the as-cast composite at different strain level in Fig. 4, there existed more flaws both in metallic glass and tungsten phase within the as-extruded composite. In addition, Fig. 4(d and f) exhibit micros-

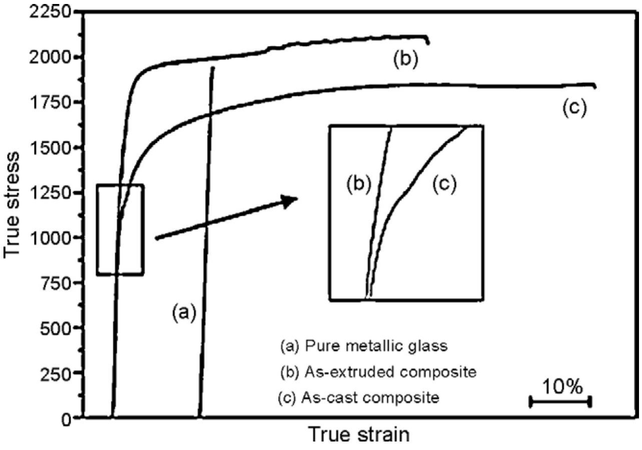

Fig. 2. Typical true stress–true strain curves for the pure metallic glass, the as-cast composite and the as-extruded composite at strain rate of $1.7 \times 10^{-3}\,s^{-1}$.