Materials Science and Engineering A 483–484 (2008) 164–167

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Deformation and damage evolution of tungsten fiber reinforced metallic glass matrix composite induced by compression

H. Zhang, Z.F. Zhang *, Z.G. Wang, H.F. Zhang

Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, PR China

Received 6 June 2006; received in revised form 6 June 2006; accepted 28 July 2006

Abstract

The deformation and damage behavior of tungsten fiber reinforced $Zr_{41.25}Ti_{13.75}Ni_{10}Cu_{12.5}Be_{22.5}$ (at.%) metallic glass composites are investigated under uniaxial compression. It is found that shear bands can form by two different modes in the metallic glass matrix. In-plane and out-of-plane shear band sliding was found in the matrix. The formation mechanisms of these two types of shear bands are explained through different degrees of lateral confinement by the fibers.

Keywords: Metallic glass; Tungsten fiber; Composite material; Deformation; Shear band

1. Introduction

Bulk metallic glasses (BMGs) have been considered as candidate materials for many potential structural applications. However, under unconstrained loading, monolithic metallic glasses usually fail with little or no plasticity, due to the rapid propagation of highly localized shear bands [1–4]. A metallic glass matrix composite reinforced by tungsten fibers has been processed, and the yield strength and ductility were reported to increase due to strengthening effect of the tungsten fiber [5]. Multiple shear bands are observed when the catastrophic instability is avoided through mechanical constrains in the metallic glass matrix in this composite [5]. This paper reports the deformation behavior of tungsten fiber composite in compression. The initiation and evolution of shear bands in the matrix under different confinements by the tungsten fiber are investigated.

2. Experimental procedures

The techniques for fabricating tungsten fiber reinforced $Zr_{41.25}Ti_{13.75}Ni_{10}Cu_{12.5}Be_{22.5}$ (at.%) bulk metallic glass matrix composites were described elsewhere [6]. Composite specimens with cross section of 3 mm × 3 mm and a height of 6 mm were cut from the cast plate for compression testing. Four side surfaces of the specimen were polished to mirror finish. From scanning electron microscopy, the volume fraction of tungsten fibers is estimated to be about 45%. The tungsten fibers in the composite specimen are parallel to the loading axis. A MTS 810 material testing machine was employed for quasi-static compression tests at a constant strain rate of $1 \times 10^{-4}\,s^{-1}$. The specimens were loaded to a pre-selected stress level and then unloaded to investigate their damage evolution. An optical microscope and a S360 Cambridge scanning electron microscope were used to observe the shear bands patterns and crack processes in the matrix and fiber.

3. Results and discussion

Fig. 1 shows the compressive stress–strain curve of the tungsten fiber reinforced $Zr_{41.25}Ti_{13.75}Ni_{10}Cu_{12.5}Be_{22.5}$ metallic glass matrix composite. Like the monolithic BMG, the tungsten composite displays elastic-perfect plastic behavior. Its yield strength is about 2 GPa which is higher than that of the monolithic metallic glass. This indicates that the tungsten fibers strengthen the metallic glass, as was observed in a fiber reinforced BMG composite [5]. The damage evolution of the tungsten composite was observed at different loading stages. The deformation was first observed at a stress level of 1.5 GPa (point A in Fig. 1), which is lower than the yield strength of its monolithic counterpart [7]. Discrete shear bands can be seen in

* Corresponding author. Tel.: +86 24 23971043; fax: +86 24 23891320.
E-mail address: zhfzhang@imr.ac.cn (Z.F. Zhang).

0921-5093/$ – see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.msea.2006.07.174

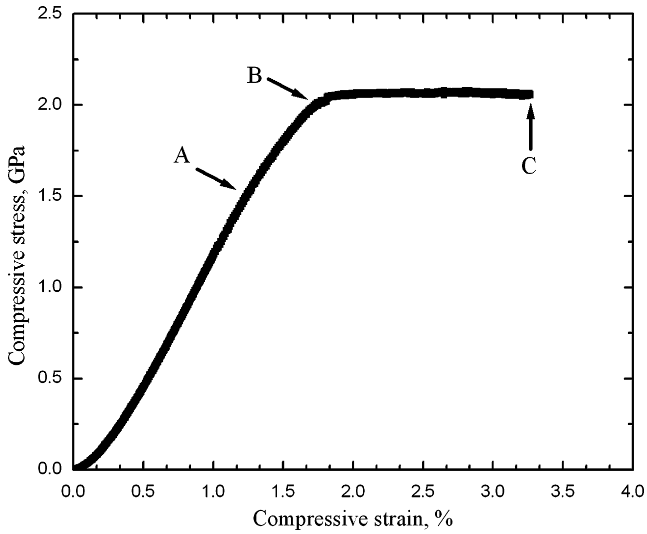

Fig. 1. Room temperature compressive stress–strain curve of tungsten fiber reinforced $Zr_{41.25}Ti_{13.75}Ni_{10}Cu_{12.5}Be_{22.5}$ metallic glass composite at a strain rate of $1 \times 10^{-4}\,s^{-1}$.

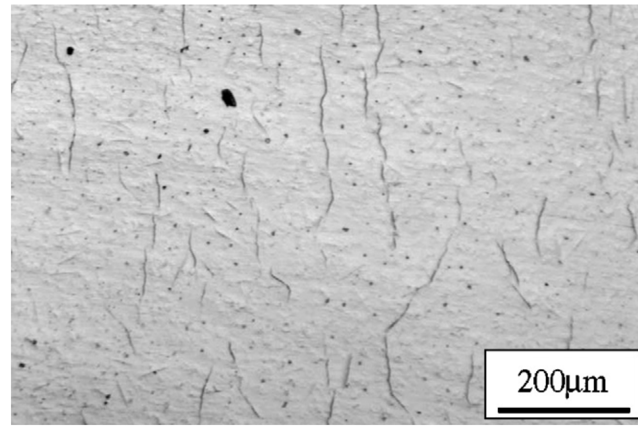

Fig. 2. Optical micrograph of tungsten composite unloaded from a stress level of 1.5 GPa showing incipient shear bands in the metallic glass matrix. The loading axis is horizontal.

the glass matrix, as illustrated by Fig. 2. These shear bands are generally perpendicular to the applied stress axis. This orientation of shear band has seldom been observed in BMG under uniaxial loading.

As the applied stress is increased to 2 GPa (point B in Fig. 1), the stress–strain curve begins to deviate obviously from the elastic slope. The number of shear bands in the matrix increases and some new shear bands appear which make angles of about 45° with respect to the applied stress axis, as shown in Fig. 3(a). In the matrix between closely spaced tungsten fibers, the number of shear band also increases. However, these shear bands are still normal to the applied stress axis, as shown in Fig. 3(b).

The specimen shows no working hardening behavior after yielding. When it is compressed further to a strain level of 3.3% (point C in Fig. 1), surface observations show the occurrence of profuse shear bands in the matrix as illustrated by Fig. 4. Some coarser shear bands are formed and microcracks can be found in these shear bands, as shown by the arrows in Fig. 4(a). Another deformation feature is that fiber splitting proceeds longitudinally near the fiber/matrix interface, indicating that there exists a strong interface bonding due to residual compressive stresses [5].

At this plastic strain, the formation of shear bands oriented at about 45° to the stress axis is the main deformation mode in the matrix between largely spaced tungsten fibers. These inclined shear bands generally propagate across the incipient shear bands, which are normal to the stress axis, as shown by the arrows in Fig. 4(b). However, in the area with small fiber spacing, the shear bands are still oriented vertical to the stress axis (Fig. 4(a)). In addition to shear band formation in the matrix, fiber splitting is another main failure mode. It is observed that the longitudinal splitting of fiber is mainly caused by impingement of the shear bands (Fig. 4(a and b)). The final failure of the composite will be either shear fracture or splitting fracture depending on the fiber volume fraction [7].

From our experimental observations of the specimen surface, the shear bands having an orientation of about 45° with respect to the stress axis, are generally observed in the matrix between largely spaced fibers when the applied stress is high. However, some of these shear bands are still normal to the applied stress in the matrix between closely spaced fibers. Deformation by shear bands or shear faults has been found in ice under biaxial compression. Different shear plane ori-

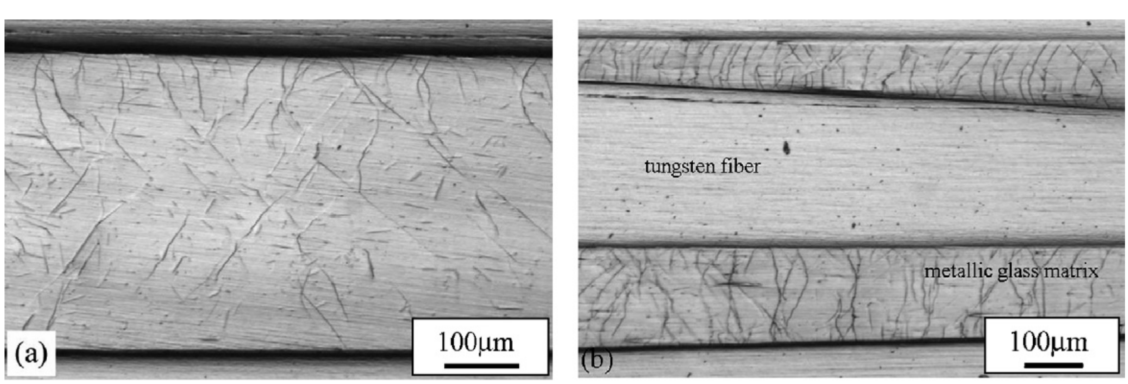

Fig. 3. Optical micrograph of tungsten composite unloaded from a stress level of 2 GPa: (a) initiation of shear bands at about 45° to the loading axis in the BMG matrix between two tungsten fibers with wide separation, (b) shear bands perpendicular to the tungsten fiber. The arrow indicates the loading direction.

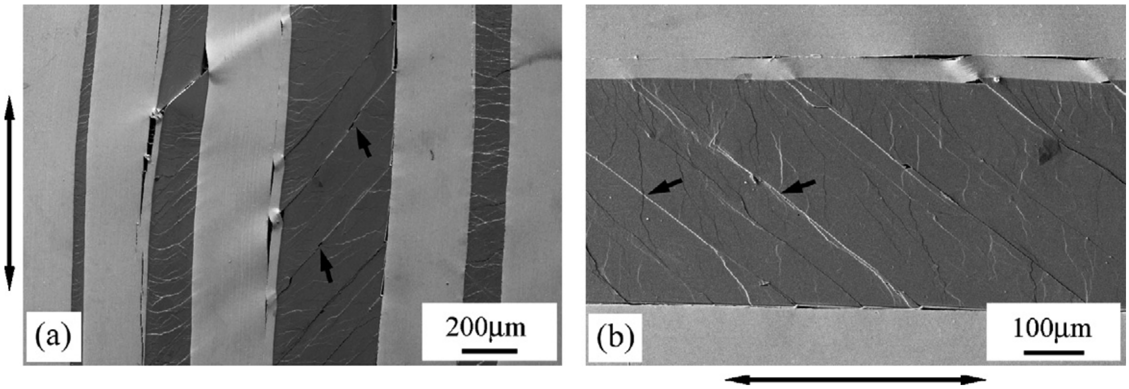

Fig. 4. Scanning electron micrographs of the tungsten composite compressed to a total strain of about 3.3%: (a) shear bands in the matrix between with different fiber separation, arrows indicate microcracks in the shear bands, (b) shear bands in the matrix and fiber splitting. Arrows indicates newly formed shear bands. In (a), the loading axis is vertical, whereas it is horizontal in (b). The long arrows indicate the loading direction.

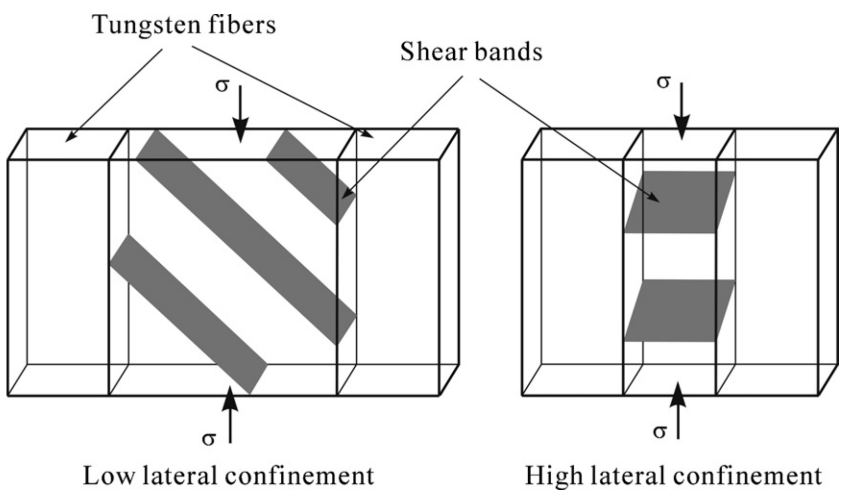

Fig. 5. Schematic illustration of shear band modes in the metallic glass matrix under different lateral confinement.

entations have been found in this case, depending upon the confinement ratio (ratio of lateral to axial stress) [8]. When this ratio is low, i.e., under low lateral confinement, shear sliding usually occurs in the loading plane, whereas at very high lateral confinement, out-of-plane sliding operates. The situation is supposed to be the same in the tungsten composite. The metallic glass between tungsten fibers is supposed to be in a state of biaxial compression during remotely applied compression and the tungsten fibers provide lateral confinement. The variation of this lateral confinement is supposed to be small during compression. In the early stage of loading, the matrix between fibers is in a high confinement state because the applied compressive stress is low compared to the lateral confinement. In this case, the shear bands in the matrix are at about 45° to the applied stress axis, but parallel to the lateral axis (Figs. 2 and 3(b)). When the applied stress increases and becomes much higher than the lateral confinement stress (low confinement ratio), the shear band in the matrix is inclined about 45° to both the applied and lateral stress axis, as schematically illustrated in Fig. 5. One may note that the fibers with small spacing always provide a high lateral confinement. Therefore, the shear bands in the matrix with small fiber spacing are in a state of out-of-plane sliding during most of the compression process.

The shear bands in the matrix, which proceed by in-plane sliding (Fig. 4(b)) generally cause shear deformation of the matrix and trigger the initiation of fiber splitting. These two deformation modes may eventually cause shear or splitting fracture of the tungsten composite [7]. Correspondingly, it is important to avoid the development of in-plane shear bands in the matrix. This suggests reducing fiber spacing, i.e., increasing the fiber volume fraction. Out-of-plane sliding of shear bands is generally not as deleterious as in-plane sliding (Fig. 4(a)). Moreover, increasing the lateral strength of the tungsten fiber is required to prevent fiber splitting as splitting is usually triggered by shear band propagation.

4. Conclusions

This investigation on deformation and damage evolution of tungsten fiber composite under uniaxial compression demonstrates that both in-plane and out-of-plane shear sliding occur in the metallic glass matrix. The formation of these two types of band depends on the degree of lateral confinement provided by the tungsten fiber. In-plane shear sliding is more deleterious and may cause shear fracture of the matrix or trigger fiber splitting, which eventually leads to failure of the composite.

Acknowledgements

We thank G. Yao, J.L. Wen, H.H. Su and W. Gao for technical assistance and stimulating discussions. This work was financially supported by the National Outstanding Young Scientist Foundation for Z.F. Zhang under Grant No. 50625103, the National Natural Science Fundation of China (NSFC) under Grant Nos. 50401019 and 50323009, and the "Hundred of Talents Project" by the Chinese Academy of Sciences.

References

[1] A. Inoue, Acta Mater. 48 (2000) 279–306.
[2] W.L. Johnson, MRS Bull. 24 (1999) 42–56.
[3] Z.F. Zhang, J. Eckert, L. Schultz, Acta Mater. 51 (2003) 1167–1179.
[4] Z.F. Zhang, G. He, J. Eckert, L. Schultz, Phys. Rev. Lett. 91 (2003) 045505.
[5] R.D. Conner, R.B. Dandliker, W.L. Johnson, Acta Mater. 46 (1998) 6089–6102.
[6] R.B. Dandliker, R.D. Conner, W.L. Johnson, J. Mater. Res. 13 (1998) 2896–2901.
[7] H. Zhang, Z.F. Zhang, Z.G. Wang, K.Q. Qiu, H.F. Zhang, Q.S. Zang, Metall. Mater. Trans. A37 (2006) 2459–2469.
[8] D. Iliescu, E.M. Schulson, Acta Mater. 52 (2004) 5723–5735.