The multifarious fracture features of the Cu-based bulk metallic glass

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Abstract: Multifarious fracture features were systematically investigated in the monolithic Cu-based bulk metallic glasses, such as coarse rive-like, micro holes, rugged and flat fracture surface. The fracture planes represent different angles with the loading direction. These fracture features are completely different from the typical fracture characteristics of amorphous alloys, i.e. vein-pattern and fracture approximately along the maximum shear stress plane. Some tiny strips with about 50 nm intervals were also detected on the flat fracture plane. The preliminary discussion on the formation mechanisms of these exceptional features were presented.

Introduction

In the last decades, bulk metallic glasses (BMGs) have received increasing attentions and have been considered as a new class of structural materials because of their excellent properties such as high strength, excellent elasticity, good corrosion resistance and wear resistance [1,2]. A large number of investigations have been carried out in terms of the glass-forming ability, mechanical and chemical properties of BMGs [3,4]. Among them, fracture behaviour of the BMG alloy is an important topic as the materials tend to fail without much plastic deformation, which largely limiting their engineering applications. So far, several fracture mechanisms have been proposed to describe the fracture of BMGs. The well-accepted theories include free-volume theory [5] and local adiabatic heating theory [6]. Recently, new investigations have been reported on fracture behaviour of BMGs. Dai *et al.* [7] suggested that both free volume coalescence and adiabatic heating softening had exert influence on the formation of shear bands and their instability in BMGs. Zhang *et al.* [8] proposed that the failure of bulk metallic glass materials followed three models, i.e. shear fracture, tensile fracture and distensile fracture. In this paper, we systematically investigate the various fracture features presented in monolithic Cu-based BMGs and correlate these features to the reported mechanisms to receive a better understand of the fracture behaviour of BMGs. One of the particular fracture features, tiny strips on flat fracture surface, is the first time being reported.

Experimental

The $Cu_{46-x}Zr_{45}Al_7Gd_2Ag_x$ (x=0, 0.5) alloys were produced by arc melting a mixture of pure alloy elements (all elements are of >99.5% purity) under a Ti-gettered Ar atmosphere. All alloy ingots were remelted four times to ensure chemical homogeneity. The ingots were then remelted in a quartz tube by induction melting, followed by casting into copper moulds with a cylindrical cavity of diameter of 2.5 mm. XRD analysis shows all samples were amorphous structures. Compression tests were performed on an Instron MTS810 at room temperature with a strain rate of 1×10^{-4} s^{-1}. The compressive specimens were 2.5 mm in diameter and 5 mm in length. Scanning electron microscopy (SEM) was used to observe the fracture surface.

Results

For the monolithic BMGs, the typical deformation behaviour is that the fracture usually occurs along the plane of maximum shear stress, which is about 45° with the loading direction, with vein pattern on the fracture surface [9-10]. Interestingly, some exceptional fracture morphologies were also observed in these Cu-based BMG materials, such as tiny strips, river-pattern and multi-angle fracture surface. .

Fig. 1 presents the macro and micro fracture morphologies of monolithic metallic glass $Cu_{46}Zr_{45}Al_7Gd_2$ alloy. Generally the fracture occurs approximately along the plane of maximum shear stress, however, the region near the surface of the cylindrical sample, some fracture planes are perpendicular to the loading axis. In terms of fracture morphology, apart of the typical vein pattern, flat fracture surface are also observed, Fig. 1b. More interestingly, in higher magnification, regular tiny strips present on these flat fracture planes (Fig. 1c and d), which have never been reported before. These strips are parallel distributed with an interval of about 50 nm. Fig. 1c shows two groups of strips with different direction. In the direction of perpendicular to the strips, ridges, which are similar to shear bands, are observed, indicated by arrows in Fig. 1d. It is should be noted that the strip characteristic is only detected in the circled region in Fig. 1b. The strips were also detected on the flat planes of fracture surface in $Cu_{47}Ti_{33}Zr_{11}Ni_6Sn_2Si_1$ BMG. The only difference is that the interval of strips is slightly large, about 54 nm.

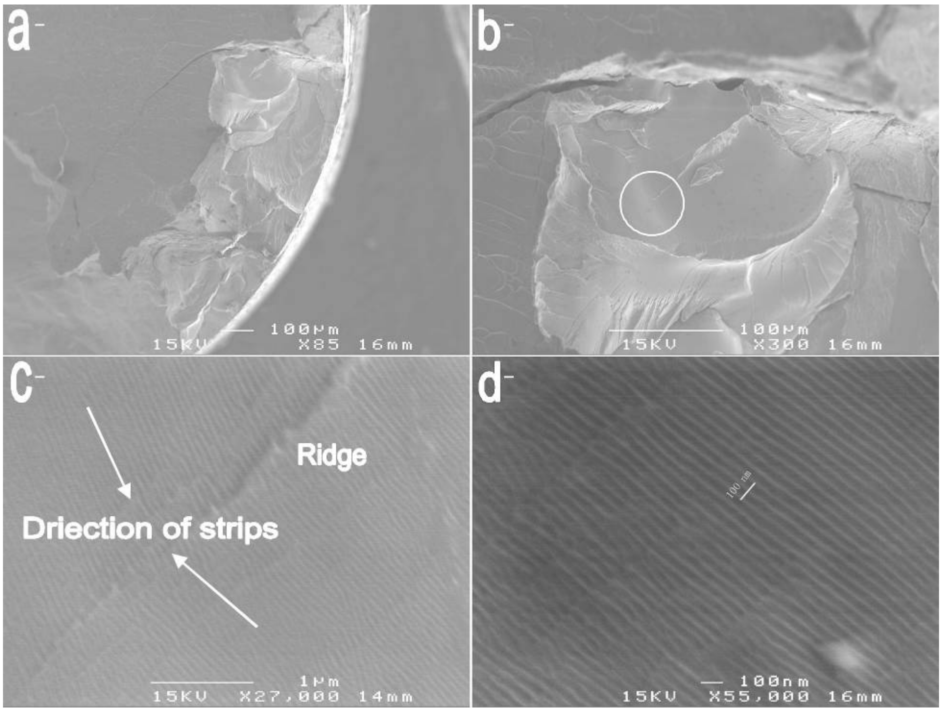

Fig. 1 Macro- (a,b) and micro- (c,d) fracture surface of $Cu_{46}Zr_{45}Al_7Gd_2$ alloy

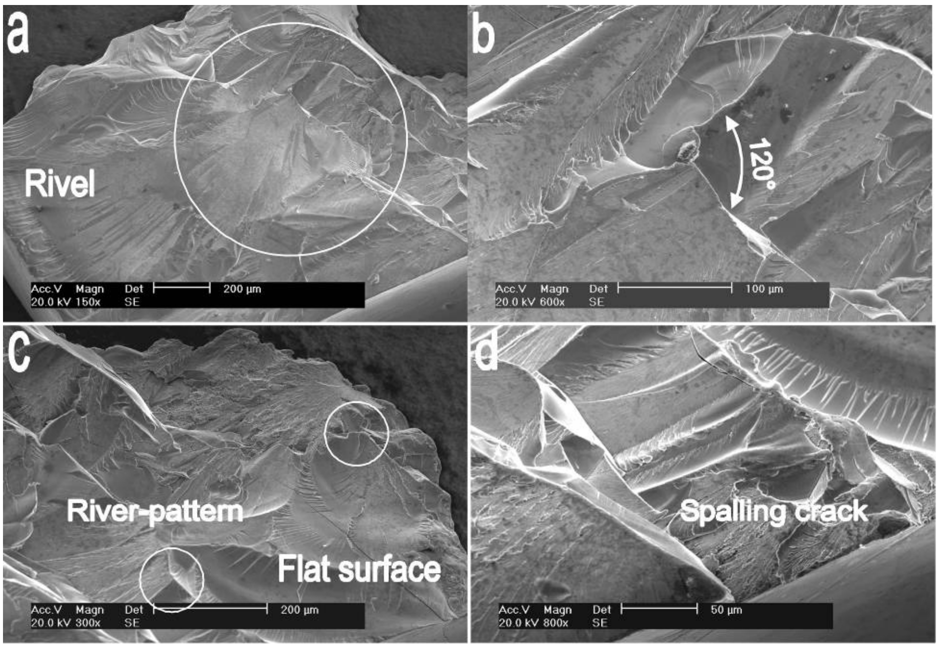

Fig. 2 Macro-fracture surface of $Cu_{45.5}Zr_{45}Al_7Gd_2Ag_{0.5}$ alloy

After the addition of Ag (0.5 at.%), the typical fracture feature of monolithic BMG is completely disappeared, although the XRD result indicates the compressive samples is amorphous structure. The samples are broken into small pieces instead of failure at one single plane after compressive test. The fracture surface becomes rough and more complicate. The fracture morphologies include river-pattern, flat plane and winkles around the flat plane, as shown in Fig. 2. The tiny strip is not observed in the flat planes of this alloy. The rough fracture surface more or less likes sharp mountains with triangle pyramid shape, illustrated by circles in Fig. 2a and b. The triangle pyramid has the axis along the loading direction and the top angle of its three planes are always about 120°. Another interesting feature is spalling crack, as shown in Fig. 2d. The crack usually appears in the region where two different fracture features meet together. The crack might relate to stress generated from the different fracture mechanisms.

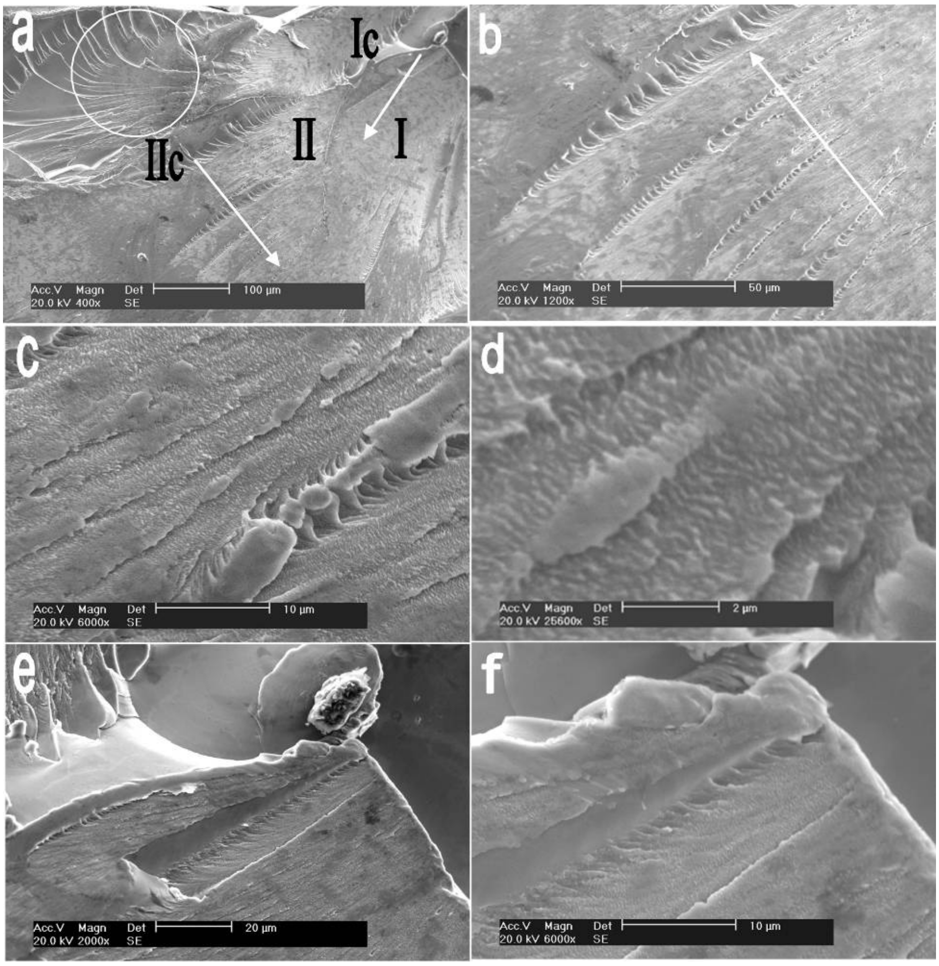

Fig. 3 Micro-fracture surface of $Cu_{45.5}Zr_{45}Al_7Gd_2Ag_{0.5}$ alloy

In these triangle pyramids, more detailed investigation is carried out. Fig 3 shows the microstructure of the triangle pyramid circle in Fig. 2a. “I” represents the primary fracture planes propagated from the top of the triangle pyramid, and “Ic” represents the primary cracks which are initiated from the top of the pyramid, Fig. 3a. The size of the cleft of the primary decreases as it travels away from the top of the pyramid. It can be concluded that the stress around the top of the pyramid is the highest. Higher magnifications of the primary cracks are shown in Fig. 3e and f. Discontinued strips and micro crack (about hundreds nanometers) are found on the primary fracture plane and inside of the primary crack. Again in Fig3. a, “II” represents the second fracture planes, which are one level away from the pyramid top, and “IIc” represents the second cracks. The second cracks increase following the arrow in Fig. 3b. It is interesting to find that the river-pattern circled in Fig. 3a are actually formed by the cleft of the second cracks, Fig. 3c and d.

Discussion

It has been pointed out by Zhang [8] that the failure behavior of a BMG material is a competitive process between shear, distensile fracture and normal tensile fracture. The final result depends on the loading mode and the homogeneity of the microstructure. During compression, stress and microstructure also interact each other. Moreover, the local high temperature aroused from energy absorption will further lead to the microstructure inhomogeneity. All these contribute to the complexity of the fracture behavior of BMG materials. As a result, the fracture plane of BMGs can occur in any angle from 0^{o} to 90^{o} with respect to the stress axis with multifarious fracture morphologies.

It is well known that the amorphous alloy has a topological structure, its packing efficiency is lower than that of the corresponding crystal, therefore more voids, namely free volume, exist in BMG structure. Under compression stress, the coalescence of the free volume finally leads to the formation of tiny strips and micro cracks. Stress also lead to a local temperature rise due to energy conversion between work and heat In some region, the localized temperature can reach the glass transition temperature, and deformation can easily occur under low stress. This is why strips usually couldn’t be observed on the primary fracture plane. On the other hand, if distensile stress plays a dominant role during compression, some strips will survive on the primary fracture plane.

The failure of Cu-Zr-Al-Gd-Ag BMGs follows distensile fracture in a break or splitting mode with fracture plane parallel to the loading direction. According to the free-volume theory, it can be deduced that merge of free volume might be responsible for the formation of large number of discontinued strips, which will then evolve to voids, and finally grow into micro cracks. The crack proceeds along different directions depending to the competition between shear, distensile stress and tensile stress. Material will fail when propagating rate of the cracks is smaller than that of deformation.

Summary

Multifarious fracture morphologies, such as coarse rive-like, micro holes, rugged and flat fracture plane, are systematically investigated in Cu-based amorphous alloys. The multifarious fracture morphologies are the result of the competition among shear, distensile stress and tensile stress during compression. The formation of tiny strip is firstly reported and might be resulted from the coalescence of free volume. While, local heat generation, together with stress during compression, will lead to most of strips disappeared.

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Reference:

[1] A. Peker and W.L. Johnson: Appl. Phys. Lett. Vol. 63 (1993), p. 2342
[2] A. Inoue, W. Zhang, T. Zhang and K. Kurosaka: Acta Mater. Vol. 49 (2001), p. 2645
[3] H.M. Fu, H.F. Zhang and H. Wang, Z.Q. Hu: Scr. Mater. Vol. 55 (2006), p. 147
[4] H.M. Fu, H. Wang, H.F. Zhang and Z.Q. Hu: Scr. Mater. Vol. 55 (2006), p. 1961
[5] F. Spaepen: Acta Mater. Vol. 25 (1977), p. 407
[6] H. J. Leamy, H.S. Chen and T.T. Wang: Metall. Trans. Vol. 3 (1972), p. 699
[7] L.H. Dai, M. Yan, L.F. Liu and Y.L. Bai: Appl. Phys. Lett. Vol. 87 (2005), p.141916-1
[8] Z.F. Zhang, G. He, J. Eckert and L. Chultz: Phys. Rev. Lett. Vol 91 (2003), p. 045505-1
[9] W.H. Wang, C. Dong and C. H. Shek: Mater. Sci. Eng. *R* Vol. 44 (2004), p. 45
[10] A. Inoue, T. Zhang, K. Kurosaka and W. Zhang: Mater. Trans. Vol. 42 (2001), p.1800