Fracture Behaviors of Metallic Glasses

Subjects: Engineering, Mechanical

Contributor: Guannan Yang

Fracture properties are crucial for the applications of structural materials. The fracture behaviors of crystalline alloys have been systematically investigated and well understood. The fracture behaviors of metallic glasses (MGs) are quite different from that of conventional crystalline alloys and have drawn wide interests.

Keywords: metallic glasses ; fracture ; shear bands ; mechanical properties, fracture mechanism

1. Introduction

Since the discovery of metallic glasses (MGs), especially bulk metallic glasses (BMGs), the mechanical behavior of MGs is attracting increasing attention for both potential structural applications and scientific interests [1]. A series of distinguished mechanical properties, including high compressive plasticity, hardness, ultimate strength, and fracture toughness have been reported [1][2][3][4][5][6][7][8]. These excellent properties and the unusual deformation mechanism of viscous flow and shear band motion make MGs a special member in the family of structural materials.

At room temperature, the deformation behaviors of MGs are controlled by shear bands, which are kinds of localized viscous flow [9]. The shear bands are very different from the slip bands formed via dislocations in crystalline alloys, and result in the special mechanical behaviors of MGs. The information about the topics of shear bands, mechanical properties, and fracture behaviors of MGs can be found in some review papers [9][10][11][12]. However, a review on the topic of how and why MGs fall out of the scope of conventional fracture mechanics is still lacking. In this article, we attempt to summarize the up-to-date understanding on this issue from several aspects about the fracture behaviors and fracture mechanism. We focus on the main fracture behaviors of metallic glasses, including the mode I fracture, brittle fracture, super ductile fracture, impact toughness, and fatigue fracture behaviors. The complex fracture mechanism of metallic glasses are discussed from the perspectives of discontinuous stress/strain field, plastic zone, and fracture resistance, which deviate from the classic fracture mechanics in polycrystalline alloys.

2. Fracture Behaviors of MGs

The fracture criterion is an important parameter to understand the deformation and fracture mechanism of a material. For MGs, due to the lack of work-hardening effect, the fracture strength in uniaxial compression tests generally will be equal to or close to the yielding strength [13]. The intensity and direction of stress at the moment of yielding or fracture reflect the critical stress condition to trigger the shear band avalanche [14][15]. From the microcosmic aspect, the yielding criterion reflects the critical stress condition to trigger the localization of shear transformation of atomic groups [16][17]. Previous studies on this issue were mostly based on the uniaxial tensile and compression experiments or simulations [18][19][20]. It has been discovered that MGs generally show a shear mode failure along a shear/fracture angle (the angle between the shear band/fracture surface and the load axis) near 45° [18][19][20]. The angle will be slightly larger than 45° under tension, and will be slightly smaller than 45° under compression. Some brittle MG systems can show cleavage or split mode failure, which will be discussed later. To understand the asymmetric compression and tension behaviors, Schuh et al. indicates that the microstructure of MGs is analogous to that of randomly packed particles in a granular solid [18]. Therefore, the yielding criterion of MGs could be described by the Mohr-Coulomb criterion:

$$\tau_y=\tau_0-\alpha\sigma_n \quad (1)$$

where τ_y stands for the shear yield stress, τ_y is a constant, σ_n is the normal stress on the shear plane, α is a coefficient that reflects the degree of internal friction in the system. This criterion explains the asymmetric compression and tension strength of MGs, but show deviations in the estimation of shear angle. On this basis, Z.F. Zhang et al. further proposed the elliptical criterion [19][20]:

$$\frac{\sigma^2}{\sigma_0^2}+\frac{\tau^2}{\tau_0^2}\geq 1 \quad (2)$$

where τ and σ stand for the shear stress and normal stress on a shear plane, τ_0 and σ_0 are material dependent constants. The elliptical criterion provides a applicable model to comprehensively explain the strength and shear angle of MGs under the simple loading condition of uniaxial compression/tension. However, the fracture behaviors of MGs under bending, fast loading, fatigue loading and other loading conditions are still complicated to be understood.

3. Fracture Mechanism of MGs

With work-hardening effect and the deformation mechanism of dislocations, the deformation of many polycrystalline alloys will experience an elastic, yielding, work-hardening, and fracture process. The mode I fracture process in these materials can be described by the classic linear elastic fracture mechanics (LEFM), which depicts the plastic zone by the contour line of yielding stress [21]. The material inside the plastic zone could deform plastically, and the material outside the zone will be still elastic. The plastic zone moves accordingly with the extension of crack-tip. The stress intensity for crack extension (fracture toughness) and energy absorption during the crack extension (fracture resistance) can be considered as material dependent constants.

References

1. Inoue, A. Stabilization of metallic supercooled liquid and bulk amorphous alloys. Acta Mater. 2000, 48, 279–306.
2. Wang, W.H.; Dong, C.; Shek, C.H. Bulk metallic glasses. Mater. Sci. Eng. R 2004, 44, 45–89.
3. Jan, S. Processing of bulk metallic glass. Adv. Mater. 2010, 22, 1566–1597.
4. Greer, A.L.; Ma, E. Bulk metallic glasses: At the cutting edge of metals research. MRS Bull. 2007, 32, 611–615.
5. Akihisa, I.; Baolong, S.; Hisato, K.; Hidemi, K.; Yavari, A.R. Cobalt-based bulk glassy alloy with ultrahigh strength and soft magnetic properties. Nat. Mater. 2003, 2, 661–663.
6. Demetriou, M.D.; Launey, M.E.; Garrett, G.; Schramm, J.P.; Hofmann, D.C.; Johnson, W.L.; Ritchie, R.O. A damage-tolerant glass. Nat. Mater. 2011, 10, 123–128.
7. Yao, K.F.; Ruan, F.; Yang, Y.Q.; Chen, N. Superductile bulk metallic glass. Appl. Phys. Lett. 2006, 88, 122106.
8. Yao, K.F.; Zhang, C.Q. Fe-based bulk metallic glass with high plasticity. Appl. Phys. Lett. 2007, 90, 061901.
9. Greer, A.L.; Cheng, Y.Q.; Ma, E. Shear bands in metallic glasses. Mater. Sci. Eng. R 2013, 74, 71–132.
10. Schuh, C.A.; Hufnagel, T.C.; Ramamurty, U. Overview No.144—Mechanical behavior of amorphous alloys. Acta Mater. 2007, 55, 4067–4109.
11. Sun, B.A.; Wang, W.H. The fracture of bulk metallic glasses. Prog. Mater Sci. 2015, 74, 211–307.
12. Xu, J.; Ramamurty, U.; Ma, E. The fracture toughness of bulk metallic glasses. JOM 2010, 62, 10–18.
13. Yang, G.N.; Chen, S.Q.; Gu, J.L.; Zhao, S.F.; Li, J.F.; Shao, Y.; Wang, H.; Yao, K.F. Serration behaviours in metallic glasses with different plasticity. Philos. Mag. 2016, 96, 2243–2255.
14. Wu, Y.; Bei, H.; Wang, Y.L.; Lu, Z.P.; George, E.P.; Gao, Y.F. Deformation-induced spatiotemporal fluctuation, evolution and localization of strain fields in a bulk metallic glass. Int. J. Plast. 2015, 71, 136–145.
15. Lan, S.; Wu, Z.; Wei, X.; Zhou, J.; Lu, Z.; Neuefeind, J.; Wang, X.-L. Structure origin of a transition of classic-to-avalanche nucleation in Zr-Cu-Al bulk metallic glasses. Acta Mater. 2018, 149, 108–118.
16. Steif, P.S.; Spaepen, F.; Hutchinson, J.W. Strain localization in amorphous metals. Acta Metall. 1982, 30, 447–455.
17. Cao, A.J.; Cheng, Y.Q.; Ma, E. Structural processes that initiate shear localization in metallic glass. Acta Mater. 2009, 57, 5146–5155.
18. Schuh, C.A.; Lund, A.C. Atomistic basis for the plastic yield criterion of metallic glass. Nat. Mater. 2003, 2, 449–452.
19. Zhang, Z.F.; He, G.; Eckert, J.; Schultz, L. Fracture mechanisms in bulk metallic glassy materials. Phys. Rev. Lett. 2003, 91, 045505.
20. Zhang, Z.F.; Eckert, J. Unified tensile fracture criterion. Phys. Rev. Lett. 2005, 94, 094301.
21. Anderson, T.L. Fracture Mechanics: Fundamentals and Applications, 3rd ed.; Taylor & Francis: Abingdon, UK, 2011.