Materials Science & Engineering A 617 (2014) 89–96

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Fracture morphology pattern transition dominated by the crack tip curvature radius in brittle metallic glasses

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ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
21 August 2014
Accepted 22 August 2014
Available online 1 September 2014

Keywords:
Metallic glasses
Fracture morphology evolution
Crack tip curvature radius
Shear transformation zone

ABSTRACT

The dynamic evolutions of different fracture morphologies in the fracture surface of brittle Mg-based metallic glasses (MGs) were systematically and quantitatively studied by SEM and AFM. It shows that the evolution of the fracture morphology pattern is dominated by an effective dynamic parameter of critical crack tip curvature radius. Based on crack tip plastic zone and shear transformation zone (STZ) theories, a theoretical model for the evolution of the crack tip curvature radius by considering the activation of STZs during fracture was proposed. The model can simulate the crack propagation process, and predict the critical crack tip curvature radius and the fracture pattern transition between the dimples and the periodic corrugations solely occurring in brittle MGs. These results have implications for understanding the microscopic fracture mechanism and the structural origin of fracture in MGs.

1. Introduction

Spatiotemporal patterns in nature, such as sweeping loops of meandering rivers, crescent and star-shaped patterns of sand dunes, and convective patterns of normal fluids, offer a direct clue to understand the dynamic behaviors of non-equilibrium systems [1–3]. The catastrophic brittle fracture of glasses, as a typical non-equilibrium process, is one of the most poorly understood fundamental phenomena in condensed matter physics [4,5]. The disordered structure makes glasses exhibit much different and unique dynamic fracture patterns compared with those of crystalline materials [6,7]. Particularly, for metallic glasses (MGs) combining the glassy structure and nature, and metallic bonds, various and plentiful dynamic fracture patterns like dimple structures [8], periodic corrugations [9], and river patterns [8] appear selectively in different regions of their fracture surface. The formation and evolution of these fracture patterns in fracture surface is a favorable fingerprint to discover the unknown crack propagation process and fracture mechanism in glasses. In addition, the micro-scale and nano-scale fracture structure such as striped structure might have potential applications in the nano-scale grating and templates. However, the key factor controlling the formation and evolution of these structures is still unclear.

The appearance of typical fracture morphology of dimple structures suggests that the microscopic plastic deformation at crack tip dominates the cracking process and the fracture pattern formation in brittle MGs. However, there is no complete theoretical scheme to understand the plastic deformation at crack tip, and the reasons for the MGs with diverse fracture toughness and completely different fracture morphology are still unknown. The plastic deformation of MGs is widely described by the cooperative shearing of atomic clusters termed shear transformation zones (STZs) [10], and the operation and proliferation of the flow units of STZs further induce the drop in viscosity and the formation of liquid-like zone at crack tip during fracture [11]. The STZ model proposed by Argon [10] and further developed by Langer et al. [12–14] is a systematic formulation of non-equilibrium thermodynamics and captures many plastic deformation behaviors in glassy materials. Recently, Bouchbinder et al. applied the STZ theory to explain the tip blunting and velocity selection in dynamic fracture [15]. Rycroft et al. used a simple version of STZ model to calculate the fracture toughness and understand the annealing-induced embrittlement of MGs [16]. The universal fractal nature of the dimple structures in fracture surface of various MGs can be illustrated properly by the athermal STZ theory [17]. These results indicate that the STZ may be considered as the microscopic deformation unit of fracture process, and the STZ theory may be used as a theoretical frame to understand the fracture pattern formation and transition in MGs [18,19].

The microscopic formation mechanism of the diverse fracture morphology in MGs remains unclear. Especially, the effective parameter which can be used to characterize the dynamic crack propagation is lacking. Previous researches on the fracture morphology evolution of MGs mainly focused on the average space or depth of typical patterns, and these parameters hardly revealed the dynamic information of the crack propagation [20–22]. Recent

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http://dx.doi.org/10.1016/j.msea.2014.08.060
0921-5093/

researches [23,24] show that the crack tip curvature radius and the crack propagation velocity are relevant dynamical variables during dynamic fracture, which could dominate the crack propagation and control the fracture pattern transition in MGs, while their relationship has been less studied experimentally and theoretically.

In this paper, the brittle $Mg_{65}Cu_{25}Gd_{10}$ MG (toughness K_C= 2 MPa $m^{1/2}$) was selected as a model system since various fracture patterns appear in its fracture surface. The fractographic evolution and the corresponding crack tip curvature radius evolution during crack propagation are investigated by a new parameter of crack tip curvature radius. We find that there exists a critical crack tip curvature radius controlling the pattern transition from the dimple structures to the periodical corrugations. A theoretical scenario based on the truncated version of the STZ theory is proposed to understand the dynamical evolution of crack tip curvature radius and the mechanism of fracture pattern transition in brittle MGs. These results might provide useful insight into the fracture mechanism of MGs and could be generally applicable to other glassy materials.

2. Experimental

The brittle $Mg_{65}Cu_{25}Y_{10}$ metallic glass ingots were prepared by induction melting a mixture of pure metal elements, followed by sucking cast into a Cu mold under argon gas atmosphere to get the plate-like specimens $5\times3\times60$ mm^3 in geometric size. The amorphous structures of the samples were identified by a Rigaku X-ray diffractometer (XRD) with Cu K_α radiation and differential scanning calorimetry. The three-point bending tests were carried out in an Instron 3384 machine (Norwood, MA) with a crosshead moving speed of 0.1 mm min^{-1} at room temperature. The bending test was repeated three times to confirm the experiment results. Specimens for pre-notched three-point bending tests had a geometric size $3\times2\times15$ mm^3. A diamond saw was used to introduce a seed notch (250 μm in width and 500 μm in depth) in the center of the plates. The newly created fracture surfaces were observed by a Philips XL30 scanning electron microscopy (SEM) instrument with the high resolution of 1.5 nm and a Oxford Instruments MFP-3D Stand Alone atomic force microscope (MFP-3D-SA AFM).

3. Results and discussion

3.1. SEM observation of fracture morphology in fracture surface

Fig. 1(a) shows the typical mirror-like fracture surface profile of the Mg-based MG. The fracture surface clearly displays the distinct river-like, mist, mirror zones along the crack propagation direction similar to previous reports [9,11,20]. The fractographic evolution sequence is the dimples in river-like zone *b* [Fig. 1(b)], the dimple and periodical corrugation mixed structures in mist zone *c* [Fig. 1(c)], and

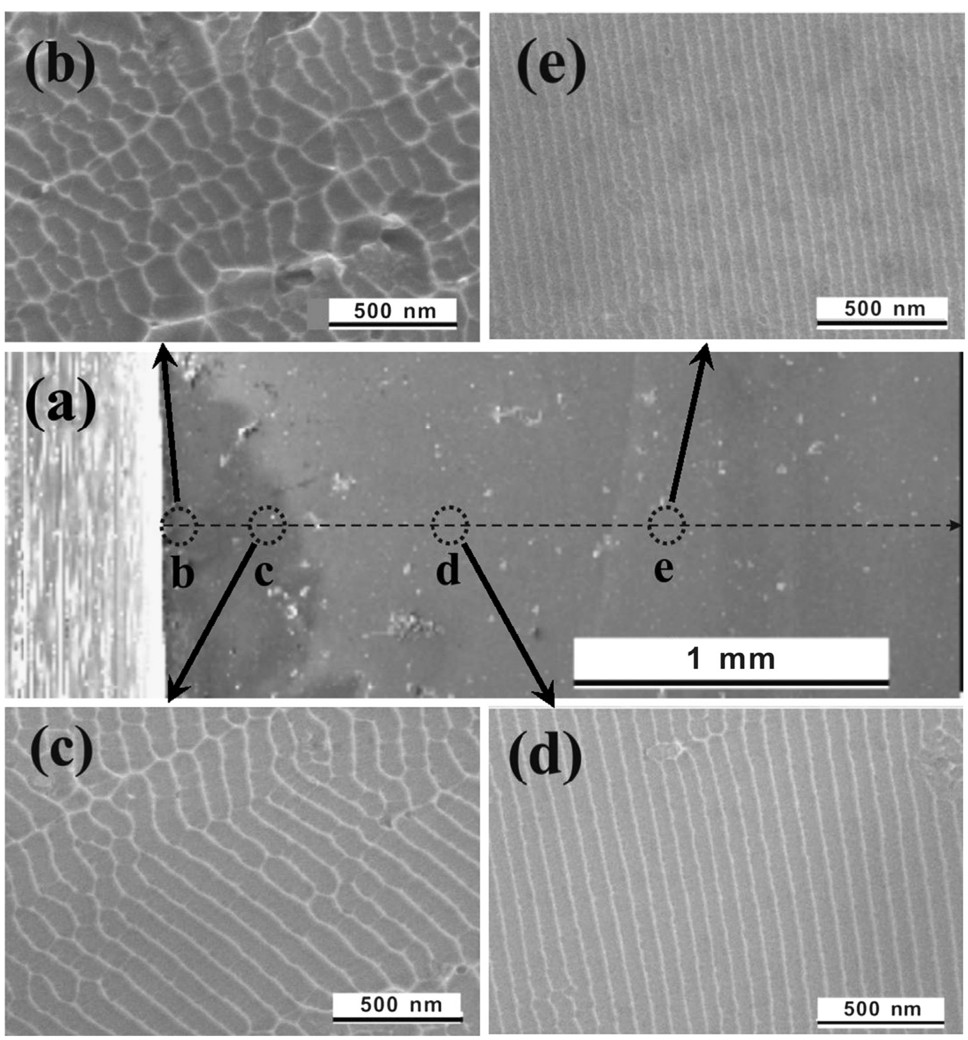

Fig. 1. (a) Overview of the fracture surface of $Mg_{65}Cu_{25}Y_{10}$ under three-point bending fracture (the dashed arrow indicates the crack propagation direction). (b)–(e) Detail morphology of zone *b*, zone *c*, zone *d*, zone *e* in (a), correspondingly.