Wavy cleavage fracture of bulk metallic glass

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Dynamic instability is one of the typical cleavage fracture features in brittle materials. The authors find that dynamic instability of metallic glass starts to occur in the mirror region on the fracture surface through a wavy cracking propagation with the formation of periodic nanoscale steps. This kind of dynamic instability is associated with the early crack curving due to the intrinsic isotropic structure of metallic glass. Furthermore, they classify dynamic instabilities of cleavage fracture as crack curving at low velocity and crack branching at high velocity, corresponding to the mirror and hackle regions of metallic glass, respectively. © *2006 American Institute of Physics*.
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Recently, dynamic fracture of brittle materials has received much attention by many investigators.[1–6] It is found that the dynamic instability induced by rapid crack propagation is one of the significant phenomena[5,7–10] and the ultimate velocity of the rapid propagating crack cannot exceed the Rayleigh wave velocity v_R.[3–5,10] Some investigators[6,7,11,12] concluded that the critical velocity v_C of a dynamic crack in brittle materials could only reach $(0.4–0.5)v_R$. When the velocity of the dynamic crack approaches the critical velocity v_C, an intrinsic instability can be observed accompanying by microscale branching.[2,4,5,7,9–12] According to dynamic fracture experiments on polymethylmetacrylate (PMMA) and glass, Johnson and Holloway[13] summarized that the fracture surface at a low cracking velocity is smooth or mirrorlike in the initial fracture region, and becomes rougher with the so-called mist and hackle morphologies if the dynamic crack velocity exceeds the critical velocity v_C.[13] In mircoscale, some investigators found that the dynamic instability consists of microbranching or bifurcations, typically in silicon single crystals[11,14,15] and SiO_2 glass.[16,17] Cramer *et al.*[11] claimed that the mirror region on the dynamic fracture surfaces is flat even on the atomic scale. This indicates that the dynamic fracture instabilities are characterized by the occurrence of mist and hackle morphologies.[2,4,5,7,9–13] Therefore, these findings give rise to some interesting questions about dynamic fracture. Whether is the initial mirror region of the dynamic fracture smooth on atomic scale or not? How does the brittle dynamic fracture become unstable if the crack is subjected to a driving force significantly larger than that required? How is the surplus of the supplied energy dissipated?

Bulk metallic glass (BMG) is one of the typical brittle materials and its fracture often occurs within a narrow shear band.[18,19] However, recently, it has been frequently observed that some Mg-, Fe-, Co-, and Ni-based BMGs (Refs. 20–24) displayed a more brittle fracture mode with many cleavage fracture regions on the fractograph under compression or bending loading. The local cleavage fracture regions on the fracture surfaces can be attributed to a relatively low cleavage strength σ_0.[25] Therefore, this provides an opportunity to reveal the dynamic cleavage fracture features of those brittle BMG materials under compression or bending tests.[22–24] In this letter, we investigate the cleavage fracture regions of $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_{5.5}$ and $Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$ BMG samples caused by compression loading using a high resolution LEO SUPER35 scanning electron microscope (SEM) with a resolution of ~1.5 nm.

Figure 1(a) displays one of the typical cleavage fracture surfaces of a large broken Fe-based BMG sample at a compressive fracture stress of 3000 MPa.[21] Normally, the fracture surface consists of three typical regions, i.e., mirror, mist, and hackle regions, as defined by Johnson and Holloway.[13] The total length of the mirror region is about

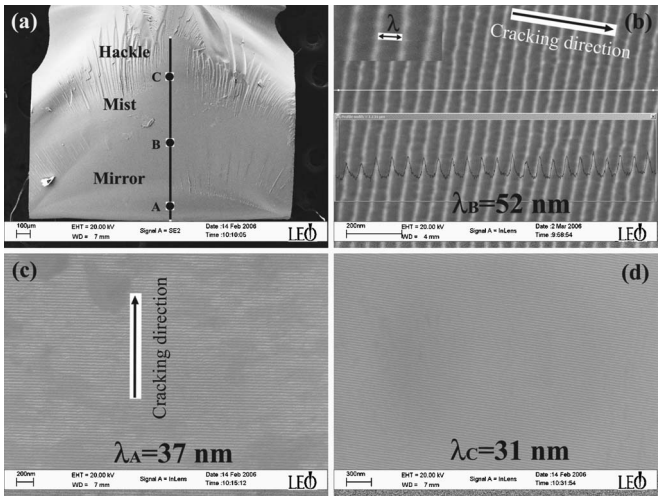

FIG. 1. (a) Brittle fracture of $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_{5.5}$ bulk metallic glass at a fracture stress of ~3000 MPa under compression. [(b)–(d)] Homogenous nanoscale steps with wavelengths of 52, 37, and 31 nm observed at the positions *B*, *A*, and *C*. respectively, in the mirror region of the fracture surface.

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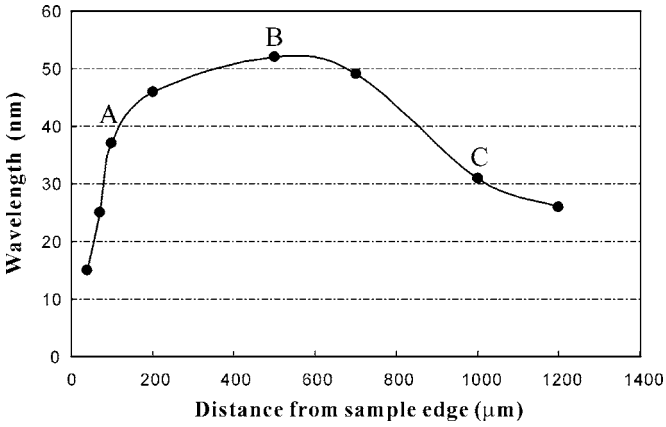

FIG. 2. Dependence of wavelength of the nanoscale steps on the distance from the sample edge.

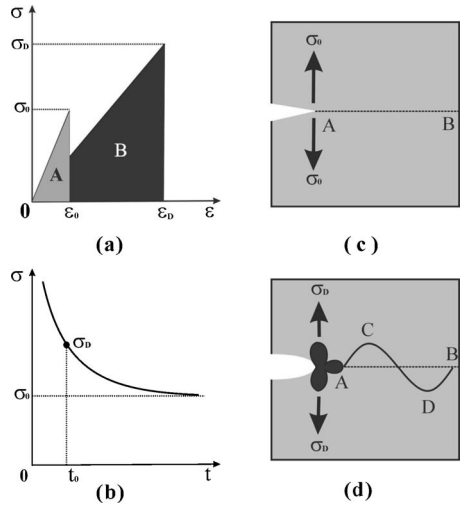

FIG. 3. (a) Illustrations of stress-strain relation for a material under static and dynamic deformation, (b) illustration of dependence of dynamic fracture strength on the fracture time, (c) illustration of a static cleavage crack propagation, and (d) illustration of a dynamic cleavage crack propagation with a hyperelastic region and a curving path.

1000 μm. The hackle region is composed of many radiating coarse steps. When we carefully observed the mirror region by high-resolution SEM, we surprisingly found that there exist actually many homogenous parallel steps, as shown in Fig. 1(b). To clarify the morphology of the fine steps in detail, position *B* in the mirror region was further scanned by secondary electron imaging. Some sharp rims or steps with nearly the same height and a periodic appearance can be clearly seen in the mirror region. The cracking propagation direction is perpendicular to these steps or rims,[23] as indicated in the figure. The wavelength λ, defined as the spacing between the two neighboring steps, is in the range of tens of nanometer, as marked in Fig. 1(b). For example, at position *B* in Fig. 1(a), the wavelength is about $\lambda_B=52$ nm. This observation indicates that the mirror region on the cleavage fracture surface is in fact not truly flat or smooth on the atomic scale, but contains many nanoscale steps. For $Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$ BMG sample, the same periodic fracture patterns can also been observed.

Figure 2 shows the dependence of the measured wavelength on the distance *L* from the sample edge along line *ABC* in Fig. 1(a). It is found that the wavelength λ near the sample edge is quite small, for example, at position *A*, $L_A=100$ μm and $\lambda_A=37$ nm [see Fig. 1(c)]. From position *A* to *B*, the wavelength monotonically increases to the maximum value of $\lambda_B=52$ nm at $L_B=500$ μm [see Fig. 1(b)], then deceases to $\lambda_C=31$ nm at position *C* ($L_C=1000$ μm), as shown in Fig. 1(d). By careful observations near the sample edge, we found that the nanoscale steps start to appear at the distance $L=40$ μm away from the edge, where the detected smallest wavelength is about 15 nm. Far away from position *C*, the fracture surface becomes very rough and corresponds to the mist and hackle regions as defined previously.[13] Those observations demonstrate that some periodic steps with a wavelength of tens of nanometers can appear in the mirror region of the cleavage fracture surface for some brittle BMGs. However, the wavelength λ of the steps does not maintain constantly, but firstly it increases from 15 nm to the maximum value of 52 nm then decreases continuously. The wavy cleavage fracture feature of the brittle BMGs is an additional failure mode in comparison with the conventional shear fracture with some veinlike patterns typically in Zr-based BMGs.[17,18]

When a brittle material fails at a static tensile stress σ_0, as shown in the shaded triangle A [Fig. 3(a)], the elastic energy density G_S stored in the material can be expressed as

$$G_S=\frac{\sigma_0^2}{2E_S}, \tag{1}$$

where E_S is the static elastic modulus and σ_0 is the static cleavage strength. When a brittle material is subjected to a dynamic loading, it was confirmed that the dynamic strength strongly depends on the fracture time,[26,27] indicating that dynamic fracture phenomenon is not instantaneous but requires a certain time. Tubler and Butcher[28] proposed a dynamic fracture criterion to formulate the time dependence of dynamic loading as

$$\int_0^{t_0}(\sigma_D-\sigma_0)^\alpha dt=\text{const an}\, t \quad (\sigma_D\geqslant\sigma_0). \tag{2}$$

Here σ_D is the dynamic strength at the fracture time t_0 and α is a material constant. The relation among static strength σ_0, dynamic strength σ_D, and necessary fracture time t_0 can be schematically illustrated as in Fig. 3(b), which was verified by dynamic experiments.[26,27]

Recently, some investigators[6,29] claimed that the elastic modulus can be considered constant only when the deformation is infinitesimally small. However, the elastic behavior observed at large strain ε_D, i.e., hyperelasticity, plays a governing role in the dynamic fracture of the local crack. Therefore, the dynamic fracture of a solid at large strain can be illustrated in the shaded triangle B [Fig. 3(a)]. Assuming that dynamic fracture occurs at a high critical stress σ_D ($\geqslant\sigma_0$), the dynamic elastic energy density G_D stored in the front of the crack tip can be expressed by

$$G_D=\frac{\sigma_D^2}{2E_D}, \tag{3}$$

where E_D is the dynamic elastic modulus at high strain rate, which is significantly lower than the static modulus E_S, i.e., $E_D\leqslant E_S$.[6,29] Therefore, there must be a big difference between dynamic and static elastic energy densities stored in the front of the crack tip, i.e.,

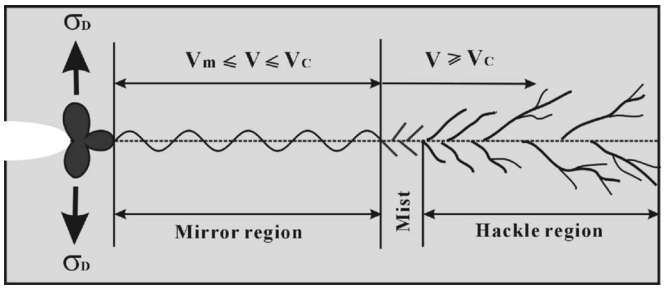

FIG. 4. Illustration of dynamic cleavage crack propagation with three typical regions, i.e., mirror, mist, and hackle. The dynamic curving occurs at a critical velocity v_m in the mirror region and terminates at the critical velocity v_C, corresponding to the formation of branching in the mist and hackle regions.

$$\Delta G = G_D - G_S = \left(\frac{\sigma_D^2}{2E_D} - \frac{\sigma_0^2}{2E_S} \right). \tag{4}$$

This indicates that dynamic fracture of a material must absorb more elastic energy than static fracture, i.e., there is an energy surplus.[11] Assuming that the surface energy γ_S per unit area of a brittle material is constant during cleavage fracture, the dynamic fracture must produce more new surfaces and makes the fracture surface rougher than under static fracture condition. Considering the fracture process of a cleavage crack in detail, as shown in Fig. 3(c), under static loading, the cleavage crack should be straight along its propagation direction from A to B, forming a smooth cleavage plane with an area of $A_0 = \overline{AB}W$ (W is the width of the fracture surface). However, under dynamic loading, the dynamic crack must dissipate more energy, which yields a rougher fracture surface, as shown in Fig. 4(d). Therefore, it is possible for the dynamic crack to propagate along a curving route of $\overset{\frown}{ACDB}$ with an area of $A_D = \overset{\frown}{ACDB}W$. Within one wavelength, the increase in the energy dissipation for surface energy due to the curving dynamic path $\overset{\frown}{ACDB}$ in Fig. 3(d) can be expressed by

$$\Delta G = 2\gamma_S(\overset{\frown}{ACDB} - \overset{\frown}{AB})W. \tag{5}$$

It is well known that the dynamic instabilities observed experimentally are always associated with the occurrence of the hackle region, for example, in single crystal silicon,[11,12,14,15] PMMA,[13] and SiO_2 glass.[14,15] By atomic force microscopy, Carmer *et al.*[11] found that the fracture surface in the mirror region of single crystal silicon is still mirrorlike or featureless even down to a length scale well below 5 nm. However, for the brittle metallic glasses, we find that the dynamic instability does happen in the mirror region, as shown in Figs. 1 and 2. Since metallic glass is structurally isotropic, the critical fracture stress or fracture surface energy along any plane should be identical. It is easier for metallic glass to induce dynamic instability at relatively low cracking velocity than other crystalline materials.[11,12,14,15] Accordingly, it is possible to observe the curving propagation path of dynamic crack with periodic nanoscale steps even in the mirror region on the cleavage fracture surface.

In summary, the dynamic instabilities of bulk metallic glass can be classified into two stages, i.e., mirror region via crack curving with periodic nanoscale steps at a low velocity v_m, and hackle region via crack branching with microscale branches at a high velocity v_C. Therefore, the propagation process of a dynamic crack can be illustrated in Fig. 4. First, the dynamic crack will make use of all possible to dissipate more energy. One easy way is to run as fast as it can, leading to a very high acceleration rate. It is believed that the critical velocity v_m corresponds to the appearance of the periodic nanoscale steps in the mirror region. With further increase in the propagation velocity v, the dynamic crack will dissipate as much surface energy as possible through a curving path, forming those periodic nanoscale steps. This propagation mode can be defined as crack curving,[30] which mainly occurs in the mirror region, as shown in Fig. 4. When the crack velocity is close to v_C, the propagation path becomes far unstable to form multiple microbranches in the front of the crack tip, resulting in the formation of the mist region on the fracture surface, as illustrated in Fig. 4. Furthermore, the microscale branches or bifurcations are developed to form the hackle region on the fracture surface. The current findings on the wavy cleavage fracture of bulk metallic glasses provide the direct experimental evidences to mechanists and physicists for a better understanding of their dynamic fracture.

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