We report the observations of nanoscale corrugation, nanowave and its branching structures on the fracture surface of tough Vit.1 bulk metallic glass (BMGs) in the supercooled liquid region. Wavelike behaviors of corrugations are observed as well. A shear band-based fracture model is proposed to interpret the formation of nanoscale morphologies in the fracture surfaces of bulk metallic glasses. The results might provide a new insight into the origin of fracture surface roughening in BMGs.

Keywords: Metallic glasses; Fracture; Shear band; Scanning electron microscopy
which is obviously larger than that observed at the room cavities with the size from 88 to 301 nm (Fig. 1(e)). The mist zone contains corelike structures (Fig. 1(d)) and a plenty of damage the fracture edge (Fig. 1(c)). The mist zone contains damage cavities (inset image corresponding to the nano-wave). These nanowaves can be severely restricted or absorbed by the thick softening medium around them (Fig. 1(d)) and demonstrate wavelike behaviors. The wavelike behaviors suggest that nanowaves are generated by the wave effect, such as perturbation waves. Microbranching is due to the crack propagation speed increasing [6]. When the crack further propagates to a critical stage, they start to bifurcate along its front and the hackle zone is formed. Except for river patterns, there are some microscopic smooth zones in the hackle zone. To examine the details of the smooth region, we amplified an area (as circled in Fig. 1(b)). The fracture surface for the enlarged section is shown in Figure 1(f). As can be seen, the localized fracture surface exhibits a profound spiral corrugation pattern, evidently demonstrating the impact of the rotated stress field. Furthermore, the spiral corrugation is sectioned by some peak-like structures along the spreading radiation. To insight the formation of the spiral corrugation, we amplified an area (as squared in Fig. 1(f)). Surprisingly, the nanoscale swirling periodic corrugations (Fig. 1(g)) are clearly observed in the present fracture surface of tough Vit.1 BMG fractured in the supercooled liquid region. The corrugation periodic length is about 70 nm (Fig. 1(i)), which is smaller than the wavelength of nanowaves in the mist zone. The reduction of wavelength indicates that the energy dissipation is increased with the acceleration of crack propagation. As the speed of cracking propagation further increased, the energy has to be dissipated by use of melting the materials in the front of crack (Fig. 1(h)). It is worth pointing out that the corrugation periodic length of the present observation is approximately equal to that observed on the fracture surface of the same BMG at room temperature [6]. This result indicates that the temperature may have little effect on the formation of nanoscale periodic corrugation. Furthermore, from Figure 1(h), one can find that the periodic corrugation is buckled to some droplets. The buckling indicates that the periodic corrugation has interfered with droplets that can be regard as the barrier in the wave propagation. The most interesting thing is that the corrugations from different directions can cross over each other and do not change their own spreading directions (Fig. 1(j)). As the arrows indicate in Figure 1(j), corrugations in different directions can travel forward along their own directions and behave like the propagation of normal waves. The curving and propagating individually of periodic corrugations suggest that the periodic corrugation is generated by certain waves again.

From the present observation and other reports [1–6], one can find that nanoscale morphologies (such as dimples, nanowaves, periodic corrugations and self-assembly cavities) can be observed in the mirror or hackle surface is parallel to the disk plane. However, the initial shearing plane in SPT is perpendicular to the disk plane. The change indicates that deformation is transformed from shear to tension model and fractured in tensile stress. The length of the fracture surface along the cracking direction is about 0.7 mm. This dimension is less than the original thickness (1.7 mm) of the disc sample. The reduction of fracture surface size demonstrates that deformation is thinning down before the sample fractured. In microscale (Fig. 1(b)), the fracture morphology shows two obvious zones: mist and hackle zones with crack propagating. Different from other reports having apparent mirror zone in the fracture surfaces of BMGs, the mirror zone is absent in the present work. Shear bands can also be observed on the polished surface near the fracture edge (Fig. 1(c)). The mist zone contains corelike structures (Fig. 1(d)) and a plenty of damage cavities with the size from 88 to 301 nm (Fig. 1(e)), which is obviously larger than that observed at the room temperature [6] on the same material under compression and plate impact tests. The presence of corelike structures (Fig. 1(d)) also provides experimental evidence of tensile stress (model I). Interestingly, nanowaves (inset image in Fig. 1(d)) can be observed clearly in some corelike structures. The wavelength is estimated about 104 nm, as shown in the inset image of Figure 1(d). The most surprising thing is the microbranching behaviors of the nanowaves along their spreading directions. These nanowaves can be severely restricted or absorbed by the thick softening medium around them (Fig. 1(d)) and demonstrate wavelike behaviors. The wavelike behaviors suggest that nanowaves are generated by the wave effect, such as perturbation waves. Microbranching is due to the crack propagation speed increasing [6]. When the crack further propagates to a critical stage, they start to bifurcate along its front and the hackle zone is formed. Except for river patterns, there are some microscopic smooth zones in the hackle zone. To examine the details of the smooth region, we amplified an area (as circled in Fig. 1(b)). The fracture surface for the enlarged section is shown in Figure 1(f). As can be seen, the localized fracture surface exhibits a profound spiral corrugation pattern, evidently demonstrating the impact of the rotated stress field. Furthermore, the spiral corrugation is sectioned by some peak-like structures along the spreading radiation. To insight the formation of the spiral corrugation, we amplified an area (as squared in Fig. 1(f)). Surprisingly, the nanoscale swirling periodic corrugations (Fig. 1(g)) are clearly observed in the present fracture surface of tough Vit.1 BMG fractured in the supercooled liquid region. The corrugation periodic length is about 70 nm (Fig. 1(i)), which is smaller than the wavelength of nanowaves in the mist zone. The reduction of wavelength indicates that the energy dissipation is increased with the acceleration of crack propagation. As the speed of cracking propagation further increased, the energy has to be dissipated by use of melting the materials in the front of crack (Fig. 1(h)). It is worth pointing out that the corrugation periodic length of the present observation is approximately equal to that observed on the fracture surface of the same BMG at room temperature [6]. This result indicates that the temperature may have little effect on the formation of nanoscale periodic corrugation. Furthermore, from Figure 1(h), one can find that the periodic corrugation is buckled to some droplets. The buckling indicates that the periodic corrugation has interfered with droplets that can be regard as the barrier in the wave propagation. The most interesting thing is that the corrugations from different directions can cross over each other and do not change their own spreading directions (Fig. 1(j)). As the arrows indicate in Figure 1(j), corrugations in different directions can travel forward along their own directions and behave like the propagation of normal waves. The curving and propagating individually of periodic corrugations suggest that the periodic corrugation is generated by certain waves again.

From the present observation and other reports [1–6], one can find that nanoscale morphologies (such as dimples, nanowaves, periodic corrugations and self-assembly cavities) can be observed in the mirror or hackle
zones on the fracture surfaces of BMGs, either the material is brittle or tough. Among these observations of nanoscale morphologies by HRSEM and AFM [1–6], some general characters can be summarized as follows: (a) the altitudes of nanoscale corrugations or dimples are <20 nm; (b) the periodicity of corrugations along the crack direction is more complete than that along the perpendicular direction; (c) the altitudes of corrugations along the crack direction is higher than that of the perpendicular direction; (d) the corrugations in the mirror zone are normally straight while they are swirling in the hackle zone. Simultaneously, transmission electron microscopy indicates that shear bands in metallic glasses are very thin, 10–20 nm [21, 22]. The thickness of shear bands is close to the altitudes of corrugations and suggests certain intrinsic correlation between the two evidences. Furthermore, shear bands usually act as precursors to brittle and ductile fracture. High-resolution transmission electron microscopy (HRTEM) also indicates that regions of shear bands in BMGs contain a high concentration of approximately one-nanometer diameter voids, which apparently result from the coalescence of excess free volume [23, 24]. Experimental measurements indicate that local temperature rise accompanying plastic deformation in the shear band of Vit.1 BMG can reach to several thousand Kelvin, which is much higher than their $T_g$ [25–27]. The fracture of BMGs in the shear band is believed in plastic model by local softening mechanism [1]. Obviously, droplet on the fracture surface (Fig. 1(h)) demonstrates that the local temperature rise in the shear band is much higher than the glass transition temperature $T_g$ of Vit.1 in the present work. So we believe that the temperature of matrix has little effect on the fracture in the shear band. The formation of nanoscale structures is tightly related to the velocity of cracking in the shear band [6, 16]. The critical cracking velocity to form nanoscale structure morphologies on the fracture surface is believed higher in the supercooled liquid region than at room temperature and is temperature dependent. This could be the reason for the observation of nanoscale morphologies in the hackle zone of the present work.

Since shear bands can be widely observed in the surfaces of fracture samples, including being fractured in the supercooled liquid region (Fig. 1(c)). They are the main characters of plastic deformation and are believed to exert significant influence on the fracture properties of BMGs. The nanoscale morphologies formation mechanism on the fracture surface of BMGs can be illustrated in Figure 2. Figure 2(a) illustrates a shear band with randomly distributed nanovoids. Under the high tensile stress without fluctuations, these one-nanometer voids freely grow into larger nanoscale voids in the shear band and the necking down or quasi-cleavage among these voids will leave vein pattern or dimple structure (Fig. 2(b) and (c)) in the fracture surface with the cracking velocity increasing. But accompanying the serration flow of shear band formation or discrete energy dissipation, infinitesimal perturbations or acoustic waves are generated, such as nanowaves of the present work (as shown in Fig. 1(d)). These perturbations will result in the formation of periodic fluctuating tensile stress filed in the shear band. As illustrated in Figure 2(d), the periodic tensile stress filed results in nanovoids preferentially growing/coalescing along the propagating direction of perturbations. Then a periodic corrugation structure is left on the fracture surface after quasi-cleavage among there nanovoids (Fig. 2(e)). It is believed that there is a critical velocity corresponding to the appearance of the nanoscale structures. The stable wavelength of the corrugation is usually in the range of tens of nanometers [1, 3, 6] due to the limitation of the thickness of shear bands. The perturbation is tended to form and propagate along the main shear banding direction that lead to cracking. So the voids are preferentially distributed periodically and the fracture in the shear bands leaves apparent periodic corrugations in the crack propagation direction. But fracture in the other direction depends on the freely necking down or quasi-cleavage behaviors and leaves less periodic corrugations. This is the main reason that the periodicity of corrugations along the crack direction is more complete than that of the perpendicular direction. The individual propagation of nanoscale perturbation wave in the mirror zone will result in the formation of periodic straight corrugation along the crack propagation. While the propagation of nanoscale perturbation wave in the hackle zone will interfere with the reflected perturbation wave from the boundary and form a rotation stress field in the shear band. The rotation stress field results in the formation of periodic swirling corrugation in the hackle zone.

In summary, we observed the nanoscale corrugation, nanowave and its branching structures formed in the shear punch fracture process of tough Vit.1 bulk metallic glass in its supercooled liquid region. The result suggests that the nanoscale morphologies on the fracture surface of BMGs are tightly related to their intrinsic structure and the plasticity nature of BMGs. We demonstrate that the nanoscale morphologies roughing is a result of local plastic fracture in shear bands. The periodic stress field induced by the stable propagation of perturbation is a key parameter for the formation of corrugation. A shear band-based fracture model is presented to interpret the formation mechanism of nanoscale morphologies ob-
served in the mirror or hackle zones of BMGs, irrespective of the tested temperature and the brittleness or toughness of materials. The result will further attract researchers’ interests in the formation mechanism of nanoscale morphologies on the fracture surface of BMGs.

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