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# Shear band-mediated fatigue cracking mechanism of metallic glass at high stress level

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ABSTRACT

The evolution processes from shear banding to fatigue cracking and fracture in $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ metallic glass were directly investigated by quasi-*in situ* cyclic compression–compression experiment. The results confirm that at high stress level fatigue crack initiated from and propagated along shear band. The cracking evolution on sample surface matches well with the different regions on the fatigue fracture surface. Furthermore, the formation of shear band and fatigue crack seems to be easier under cyclic loading than that under monotonic compression.



## 1. Introduction

Metallic glasses (MGs) have been considered as potential structural materials for many years due to their superior strength and high hardness, excellent corrosion resistance and high wear resistance [1,2]. However, the fatigue strength of MGs is unexpectedly low. It is reported that the fatigue endurance limits of some MGs are only as low as 5–20% of the ultimate tensile strength (UTS) [3–8], while high-strength crystalline materials usually exhibit fatigue endurance limits roughly equal to half of their UTS [9,10]. Meanwhile, the fatigue strengths of MGs were reported to vary in a wide range by different authors even for alloys with identical compositions [6–8]. Consequently, it is very necessary to investigate the fatigue cracking mechanism to clarify the inherent reasons of the fatigue performance.

Although abundant experimental and simulation studies have been conducted to study the fatigue behaviors of various MGs [11–22], the fatigue cracking and fracture mechanisms are still not well understood. For crack initiation, it is proposed that there are two kinds of cracking origins: pre-existing defects and shear bands. In contrast to pre-existing defects [11–15], although shear band has been frequently considered as the deformation media for fatigue failure [16–22], direct evidences for shear band as origin of fatigue cracking are still not sufficient. On the other hand, shear band usually appears at stress near the yield strength of MGs under monotonic compressive loading [23], which implies that shear band is not necessarily the cracking site under cyclic compression with stress level much lower than the yield strength. Accordingly, some fundamental questions arise: Can shear band form below the yield strength under cyclic loading condition? And is shear band the origin of fatigue crack, or the result from the fatigue cracking? In the present work, in order to answer these questions, quasi-*in situ* compression–compression fatigue experiments at high stress level were employed. Crack initiation, propagation as well as shear banding processes were directly observed at different stages of the fatigue test. Compelling experimental evidences were finally obtained for the shear band-mediated fatigue cracking mechanism in MGs.

## 2. Experimental

$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ MG plates with dimensions of $60 \times 30 \times 3\ mm^3$ were prepared by copper mold casting in a high-purity argon atmosphere. The amorphous structure was identified by X-ray diffraction (XRD). Specimens with dimensions of $2 \times 2 \times 4\ mm^3$ for cyclic compression–compression tests were cut from the MG plates by an electric spark cutting machine. The specimens were ground and polished by 2.5 μm diamond paste. The fatigue tests for a selected specimen were periodically conducted under the stress control mode by using an Instron 8801 testing machine at room temperature. The ratio of the maximum applied stress $\sigma_{max}$ (1500 MPa) to the compressive fracture strength $\sigma_C^F$ (1800 MPa) is 0.83, and the stress ratio $R = \sigma_{min}/\sigma_{max} = 0.1$. A sinusoidal wave with a frequency of 20 Hz was employed for the fatigue tests. After certain cycles, the testing specimen was

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unloaded and the fatigue damages were examined with a LEO Supra 35 scanning electron microscope (SEM). Subsequently, cyclic compression–compression test on this specimen was resumed. In order to observe the evolution of shear bands and fatigue cracks directly, a quasi-*in situ* process (loading…unloading…observing…) was repeated several times until the specimen fractured. The fatigue fracture morphologies were also observed with SEM.

## 3. Results and discussion

Fig. 1 displays the fatigue damage process under cyclic compression–compression loading. The fatigue damage morphologies on two adjacent faces of the sample after 5000 cycles are shown in Fig. 1(a) and 1(b), respectively. Shear bands with distinct shear step at sample edge can be seen, while no crack is observed at this stage. This result demonstrates that under cyclic deformation at high stress level shear band emerges prior to the formation of fatigue crack. In addition, the angle between the shear band plane and the loading axis is ~42°, which is smaller than 45° and similar to that under monotonic compression [24]. On another surface of the fatigued sample, surprisingly, profuse shear bands are observed, as indicated by the arrows in Fig. 1(b). In contrast to the few shear bands observed in samples after monotonic compression [25–28], the high-density shear bands in the sample after cyclic deformation implies that shear band may be easier to initiate under cyclic loading condition than that under monotonic loading. This is consistent with the molecular-dynamics simulation by Cameron and Dauskardt [29], who found that cyclic loading increases the free volume levels and accelerates the formation of shear bands.

After 8000 cycles, fatigue cracks can be readily observed in the major shear band (MSB), as shown in Fig. 1(c) and (d). It seems that the fatigue crack initiates from the onset of the MSB. Away from the start of the MSB, the main crack gradually becomes closed and some microscale cracks appear ahead of the main crack tip, as exhibited in Fig. 1(d). With further cyclic deformation to 12,000 cycles, one can see the propagation of the main crack along the shear band (Fig. 1(e)). The microscale cracks and the uncracked part of the MSB in Fig. 1(d) have eventually cracked and merged into the main crack. These results indicate that the fatigue crack at high stress level may probably initiate from the start of the MSB and propagate along the MSB progressively. Fig. 1(f) shows the magnified image of the region ahead of the main crack tip in Fig. 1(e). It can be seen that secondary shear bands and secondary cracks have emerged from the MSB. After cyclic loading to 18,000 cycles, the surface damage becomes rather serious, as displayed in Fig. 1 (g) and (h). Both the main and the secondary cracks become longer and wider. And the region between the secondary shear bands and the MSB has been protruded, as indicated by the white arrows in Fig. 1(h). Finally, the sample fractured at 20,000 cycles along the

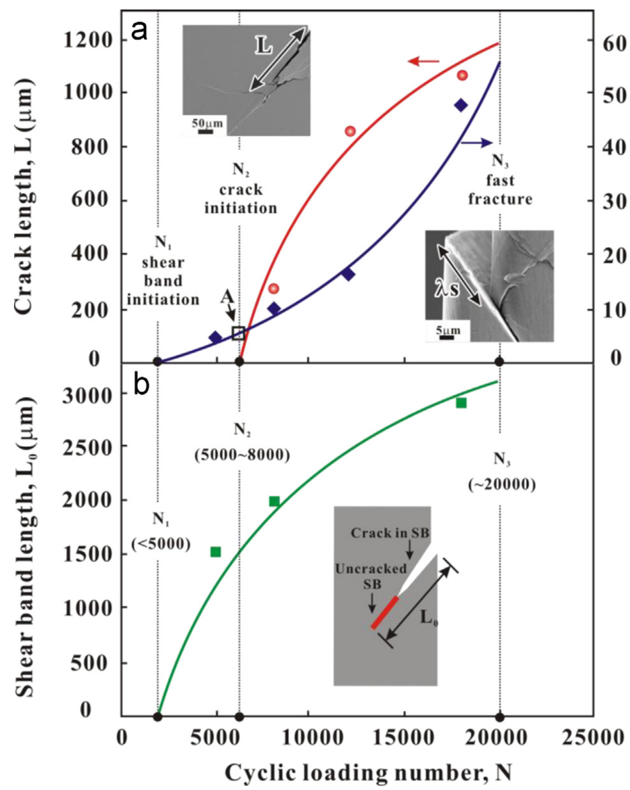


**Fig. 2.** (a) Relationship between the length of the main fatigue crack $L$, the shear offset $\lambda_s$ at the start of the MSB and the cyclic loading number $N$; (b) relationship between the shear band length $L_0$ and the cyclic loading number $N$.

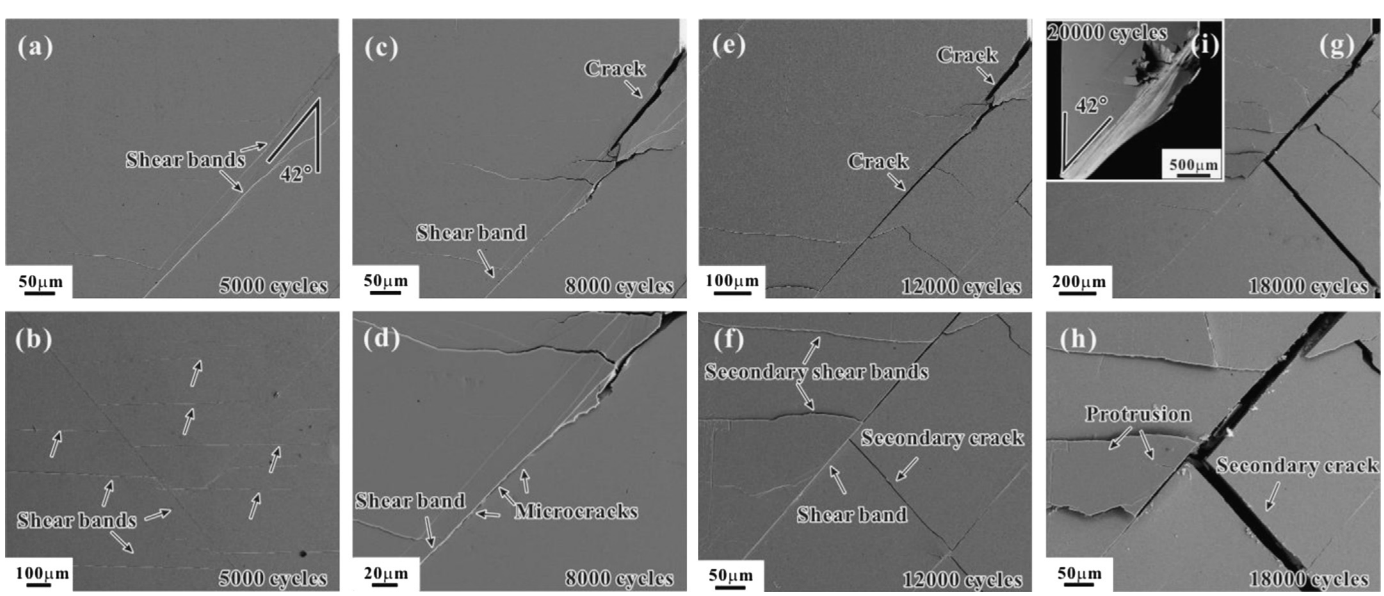


**Fig. 1.** Fatigue damage morphologies under different cycles with $\sigma_{max}=1500$ MPa and $R=0.1$: (a) (b) $N=5000$ cycles; (c) (d) $N=8000$ cycles; (e) (f) $N=12{,}000$ cycles; (g) (h) $N=18{,}000$ cycles; (i) $N=20{,}000$ cycles.