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Crack Propagation in Metallic Glass Ribbon as a Function of the Position of Stress Concentrators

Mária Huráková^{1, a*}, Kornel Csach^{1, b}, Jozef Miškuf^{1, c}, Alena Juríková^{1, d},
Václav Ocelík^{2, e} and Jeff Th.M. De Hosson^{2, f}

¹Institute of Experimental Physics, Slovak Academy of Science, Watsonova 47, 040 01 Košice, Slovakia

²Department of Applied Physics, Faculty of Mathematics and Natural Sciences, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

^{a,*}hurakova@saske.sk, ^bcsach@saske.sk, ^cmiskuf@saske.sk, ^dakasard@saske.sk,
^ev.ocelik@rug.nl, ^fj.t.m.de.hosson@rug.nl

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Abstract. An amorphous metallic ribbon of Fe₄₀Ni₄₀B₂₀ was used for in-situ observation of the crack propagation and shear band formation during tensile tests. Prior to the tensile tests, two holes (with different positions with respect to the tensile axis) were made by laser ablation as stress concentrators. The nucleation and propagation of shear bands on the ribbon surface during tensile tests were analysed with scanning electron microscopy (SEM). At room temperature inhomogeneous plastic deformation of amorphous alloy occurs via the development of primary and secondary shear bands. The influence of the different loading geometry on the topology of shear bands and crack propagation was studied.

Introduction

The metallic glasses exhibit several unique deformation phenomena due to the predominance of shear banding at low temperature deformation. Due to the lack of long-range order in the atomic amorphous structure, plastic deformation of metallic materials is completely different from its crystalline counterpart [1, 2].

Spaepen [3, 4] argued that the deformation in a randomly packed assembly such as a metallic glass is associated with dilatation and breakdown of an ordered structure due to diffusional processes at a local atomic scale. Under loading free volume is created when the atom squeezes into a neighbouring free volume site with slightly smaller volume and the annihilation occurs by the structural rearrangement [3, 4]. At low temperature the free volume can be accumulated in some regions of the shear what leads to the significant softening causing shear localization near the planes of maximum shear stresses and hence inhomogeneous flow [5]. It is generally accepted that different levels of free volume lead to the differences in the resulting mechanical behaviour of the amorphous materials. At loading the plastic deformation is accumulated in the area near the crack tip and the system of shear bands is created. These bands lie near the plane of maximal shear stresses at the angle of 45° with respect to the applied tension axis [6, 7].

Due to the lack of the work hardening metallic glasses are very sensitive to failure under tensile loading and have the tendency to instability. In fact, metallic glasses at lower temperatures are deformed predominantly through the localization process. Under tensile loading of metallic glasses the tendency to failure can be observed. The creation of the shear bands and crack instabilities is apparently governed by the local structure and elastic properties of the solid [8, 9].

In this paper we will focus on the in-situ observation of the inhomogeneous plastic deformation process in Fe-based metallic glass ribbon during the tension loading of the ribbon samples with stress concentrators at various locations using scanning electron microscopy.

Experimental

The samples of the amorphous metallic ribbon with a nominal composition of $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{20}$ (at. %) with the cross-section of $10 \text{ mm} \times 0.018 \text{ mm}$ were prepared by rapid melt quenching on a spinning metallic disc. Into each sample with a length of 40 mm two holes as stress concentrators were made by a pulse laser with a beam diameter of $120 \text{ }\mu\text{m}$. The holes in individual samples were positioned at equal distance of $300 \text{ }\mu\text{m}$. The angles between the normal plane to the tensile axis and the link of the holes were 0° , 22° , 45° as Fig. 1 demonstrates.

In-situ uniaxial tensile deformation experiments for different stress concentrator geometries were performed with a loading rate of $3 \text{ }\mu\text{m.s}^{-1}$ using loading stage Kammrath & Weiss installed in the chamber of the scanning electron microscope XL30 ESEM-FEG. Shear bands on the ribbon surface during the tensile tests were observed. The created fracture surfaces in the area of holes after in-situ tensile tests were studied using a scanning electron microscope Tescan VEGA 3 LMU.

Results and Discussion

The tensile curves from in-situ loading experiments for different positions of the holes are shown in Fig. 2. Upon increasing applied load the elongation of the samples increases. At a given stress the elongation depends on the position of the holes; as the angle decreases, the measured elongation increases. For 0° position of the holes the failure of the sample occurred at the tensile stress approximately of 600 MPa, for 22° at 1000 MPa and for 45° positions of the holes the failure occurred at 900 MPa. All the samples fractured by the premature failure in the tension grip area.

Fig. 1 Scheme of samples with different stress concentrators for in-situ tensile tests

Fig. 2 Tensile curves for various positions of the holes

It can be expected that the specific location the holes (0° , 22° and 45°) affects the normal and shear stresses on the crack propagation. The microscopic observations were focused on the region around the holes and on the area between them. As the first shear band was observed, the loading was paused and the SEM image of the area of the interest was recorded. The first shear band appeared at the loading of 40 N, 36 N and 31 N for the samples with loading angles of 0° , 22° and 45° , respectively. The decrease of the loading of the first shear band appearance is controlled by effective projected load.

The documentation of the in-situ tensile test of the sample with 0° position of the as a function of load is shown in Fig. 3. Generally, the holes prepared by the impact of the laser pulse go through the sample thickness and are irregular in the shape. Around the holes in the heat-affected zone is remelted material.

Fig. 3 The formation and propagation of shear bands during in-situ tensile test at 0° position of the holes

Fig. 4 Detailed propagation of shear bands in the area of left hole during in-situ tensile test at 0° position of the holes

At the load of 40 N the first crack was created near the left hole outside the area between holes as the arrow in Fig. 3 indicates. Upon increasing load to 52 N, the crack appeared at the opposite side of the same hole. At a load of 65 N the cracks appeared at the right hole at opposite sides. A detailed view of the shear band pattern evolution at the crack tip (marked by the circle in Fig. 3) with increasing loading can be seen in Fig. 4. The increase of the loading from 65 N to the value of 100 N is connected with widening of the crack. The deformation occurs via the shearing in the existing shear bands as well as by generation of new shear bands due to the local stress fields. Finally the increase of the loading to the value of 107 N dramatically changes the appearance of the deformed area. The last frame in Fig. 3 shows the jagged margin of the right hole. The crack visible at previous frames (up to 100 N) and in detail shown in Fig. 4 vanished. A detailed analysis of the crack tip at the load of 107 N on the last frame in Fig. 4 shows that the primary crack moved in a jerky fashion and a new crack is generated. By this way the accumulated elastic energy is released, the main crack width decreases and the local curvature of the thin ribbon is changed. The crack evolution with the loading increase is shown in Fig. 5. Due to a decreasing crack width the trace of the crack in the last frame of Fig. 3 is difficult to find.

Fig. 5 The crack propagation with the loading increase

Fig. 6 The formation and propagation of shear bands during in-situ tensile test at 22° position of the holes

Fig. 7 Evolution of the shear band pattern under indicated loadings; corresponding crack tip is in Fig. 6 marked by the circle

The formation and the propagation of the shear bands at different stresses and for the 22° position of the holes are illustrated in Fig. 6. At a load of 42 N cracks (marked by the arrows) at both sides of the right hole were observed. With increasing load cracks on the opposite hole appeared. The deformation zone at the crack tip marked on the fourth frame of Fig. 6 by the circle was examined in detail and is shown in Fig. 7.

The cracks are generated in the heat-affected zone and propagate very rapidly. The crack propagation is carried out via fracture mode I (opening mode). In the virgin amorphous area the crack is stopped and shear bands are generated in the larger area. During this stage, the fracture mode II (sliding mode) of the deformation acts and steps on the surface are observed. With a further increase of loading deformation occurs via the nucleation of new shear bands and via shear deformation.

The deformation behaviour at the hole position of 45° is shown in Fig. 8. The first cracks were generated at a load of 31 N at the opposite sides of the left hole as it is marked by arrows in the third frame of Fig. 8. As the loading increases, new cracks are appeared at the opposite sides of the right hole.

Fig. 8 The formation and propagation of shear bands during in-situ tensile test at 45° position of the holes

Fig. 9 Detailed propagation of shear bands in the area of the right hole during in-situ tensile test at 45° position of the holes

Detailed observation of the crack tip area morphology at increasing the load is shown in Fig. 9. The selected crack is marked in Fig. 8 on the fourth frame by the circle. With increasing load the shear band pattern exhibits a more regular form. The shear bands generated after stopping of catastrophically propagated crack (observed at 49 N) are unchanged during the next increase of load. As the loading increases to the value of 125 N plastic deformation occurs via the nucleation of a new shear band. At the final stages of loading, the shear deformation proceeds by shearing along properly oriented shear bands. Crack branching is shown in the last frame of Fig. 9.

In all cases premature failure occurred near the grips. For observing the final crack surface we broke the samples by bending in the area of the holes. The hole area is shown in Fig. 10 (left). The holes are surrounded by a smooth curved surface. The failure initiated in the heat-affected zone is shown in Fig. 10 (right).

Fig. 10 The hole area after breaking (left) and a detail of fractured area with the crack (right)

The high energy of the laser pulse was consumed by evaporation, melting and residual heat spread into the parent material. The smooth curved area is the melted and cooled material. The size of the heat-affected zone can be estimated by fractographic analysis. Fig. 10 right reveals that the cracks are generated in the brittle heat-affected zone.

Conclusion

In-situ tensile test of Fe-based amorphous alloy showed that plastic deformation was localized in the area around the holes. The primary cracks are generated in the heat-affected zone under normal stresses and the shear bands are generated at the crack tip and propagated under shear stresses. The position of holes does not influence the shear band patterns.

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