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Effect of the stress ratio on the fatigue behavior of $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass. Part II — Reconfirmations and new findings on the crack propagation mechanism

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ABSTRACT

The assessment of the reliability of Bulk Metallic Glasses (BMGs) as structural materials needs further investigations, particularly dealing with the impact of the loading condition on the fatigue behavior. Stress ratio *R* is one of these important parameters associated with the fatigue loading. The present work investigates the high-cycle fatigue properties of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG at three distinct stress ratios from 0.1 to 0.7. Even though Part I of the present study has been mainly focused on the fatigue resistance considerations, a peculiar feature was found on the fracture surface at stress ratio of $R = 0.7$. Thus, this second part is investigating the fatigue crack propagation behavior of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG. Experimental results highlight a crack propagation behavior at $R = 0.1$ and 0.4 similar to the results reported in the research field. On the other hand, observations of fracture surface and tensile surface of specimens failed at high stress ratio of $R = 0.7$ underline a peculiar crack propagation behavior.

1. Introduction

Due to its very interesting properties, such as high yield stress and high elastic strain limit [1–3], BMGs are likely to fulfill the requirements for structural applications. However, BMGs are also known to show particularly low fatigue endurances. Indeed, the ratio of fatigue limit over the tensile strength does not exceed usually a value of 20% [4–7]. Such a trend has been reconfirmed for $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG studied in Part I [8] of the present study. Even though numerous works have discussed the effect of testing procedures [9–12] or environment conditions [13–16], effect of the stress ratio R ($= \sigma_{min}/\sigma_{max}$) needs to be more deeply investigated. In the present work, effect of stress ratio up to a value of 0.7 on the fatigue properties and crack propagation behavior of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG has been examined in various viewpoints.

In this second part, discussions are dedicated to the fatigue crack propagation behavior at the three different stress ratios investigated $R = 0.1$, 0.4 and 0.7. The crack propagation was measured by a newly developed in-situ observation system. Experimental results obtained underline similar crack propagation phenomena at $R = 0.1$ and 0.4 in agreement with the discussions reported in the research field. However, some irregularities are found at $R = 0.7$. After conducting a detailed analysis of the crack features found on both fracture and tensile surfaces, a model is proposed to understand the configuration of the so-called "gutter-like" pattern pointed out in Part I.

2. Experimental procedures

Before introducing peculiar procedures dedicated to crack propagation experiments, authors point out that most of the experimental procedures in the present report are exactly the same to Part I of this study. Indeed, the raw material, the specimen preparation and the fatigue testing conditions are already described in Part I article [8].

2.1. Observation of specimens after fatigue tests

Observations of failed specimens were undertaken using Hitachi SU6600 SEM at a 20 kV acceleration voltage setting. For detailed analysis, three dimensional reconstructed images of the fracture surface were conducted by Mex 5.1 software (developed by alicona imaging GmbH), based on three distinct SEM photographs taken at tilt angles of −5°, 0° and 5°.

The micrographs used for analysis of the shear band spacing on the tensile surface of the specimens were obtained by Optelics Hybrid L3

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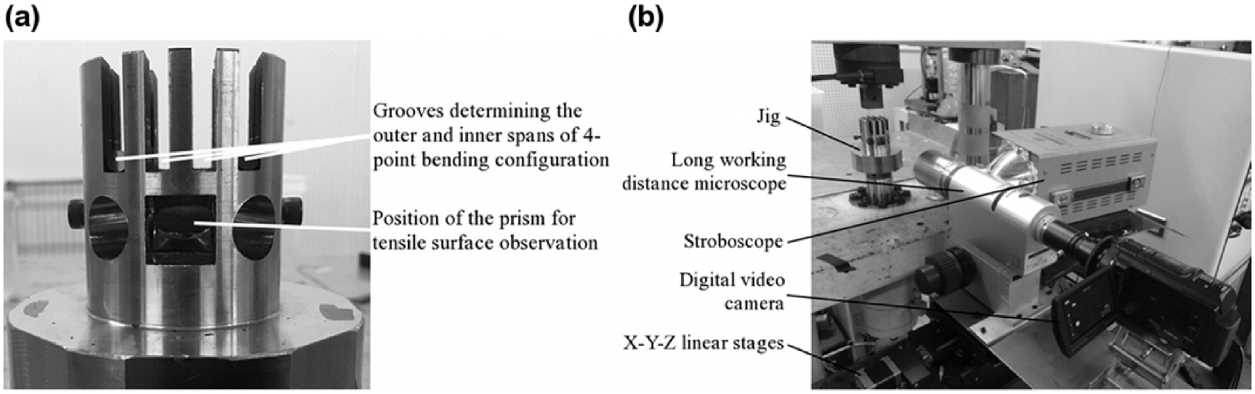

Fig. 1. Developed in-situ crack observation system. (a) Jig equipped with a prism to reflect tensile loaded surface image and (b) Capture system of the reflected image.

laser microscope, manufactured by Lasertec Corporation.

2.2. In-situ crack observation system

In the present study, the crack propagation behavior of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG is analyzed by using a newly developed in-situ crack observation system introduced in Fig. 1. This system continuously records the specimen's tensile surface through the entire fatigue test duration to analyze propagation of the fatigue crack.

The actual jig used for four-point bending fatigue test is presented in Fig. 1(a). On the upper side of the jig, one can notice the grooves corresponding to the position of the rods to perform fatigue tests. On the lower part of the jig, a prism has been introduced in order to reflect the image of the specimen's tensile surface. This reflected image then has to be enlarged and properly captured in order to be able to analyze it. The several devices dedicated to image capture are depicted in Fig. 1(b). In order to enlarge the source image, a Union UWZ200 long distance microscope with a magnification factor of 200 × is used. Nevertheless, clear observation of the specimen surface requires very intense light flashes, obtained by a stroboscope. The stroboscope flash is synchronized with the load cell signal in order to catch the tensile surface when maximum stress is applied on the specimen. Obtained image is then recorded by a digital video camera. However, such a system alone monitors only a small fraction of the whole area in pure bending loading condition. To overcome this difficulty, a X-Y-Z motorized stage was added to perform the observation of the whole area by reassembling images obtained from different locations. In the present study, the entire tensile loaded area is scanned by the means of 108 distinct photographs.

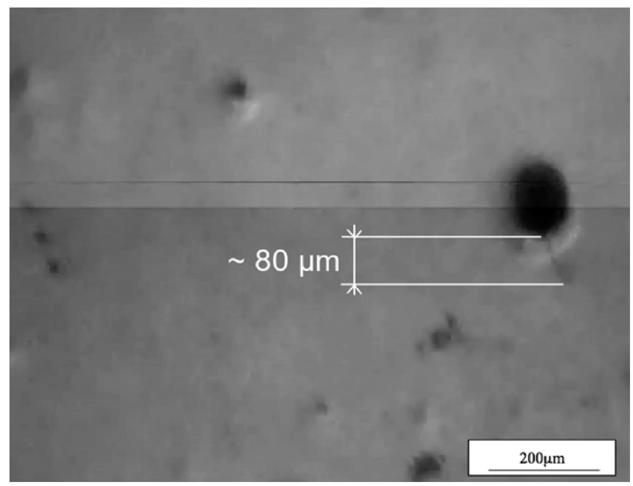

Fig. 3. High magnification micrograph for tiny crack detection at $N = 3811$ cycles, $\sigma_a = 600$ MPa, $R = 0.4$.

An overview of the observation resolution of the fatigue crack using the developed system is given in Figs. 2 and 3. The initial condition of the specimen's tensile surface is presented in Fig. 2(a), thus before the crack is initiated. At $N = 3811$ cycles, Fig. 2(b) shows the initiation of a tiny crack close to a small defect. According to Fig. 2(c) and (d), the crack then propagates through the tensile surface as number of loading cycles increases. The last record before final failure of the specimen is depicted in Fig. 2(e), at $N = 14,346$ cycles. In order to grasp more

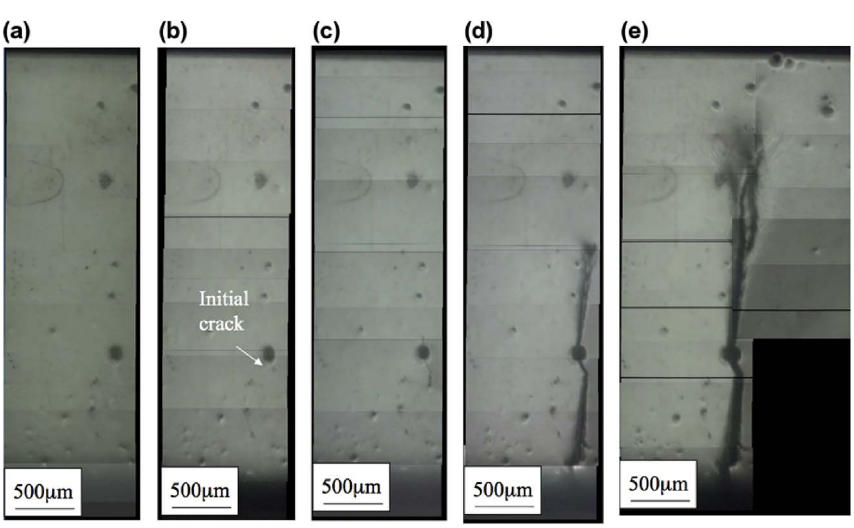

Fig. 2. Overview of in-situ crack observation system performances for a fatigue test at $\sigma_a = 600$ MPa, $R = 0.4$, $N_f = 14,494$ cycles. (a) Initial condition of the tensile surface at $N = 0$; (b) First detection of the crack at $N = 3811$ cycles; (c) Early crack propagation state at $N = 8321$ cycles; (d) Crack propagation at $N = 13,437$ cycles and (e) Final record before failure of the specimen at $N = 14,346$ cycles.