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Modeling size effects on fatigue life of a zirconium-based bulk metallic glass under bending

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Abstract

A size effect on the fatigue-life cycles of a $Zr_{50}Cu_{30}Al_{10}Ni_{10}$ (at.%) bulk metallic glass has been observed in the four-point-bending fatigue experiment. Under the same bending-stress condition, large-sized samples tend to exhibit longer fatigue lives than small-sized samples. This size effect on the fatigue life cannot be satisfactorily explained by the flaw-based Weibull theories. Based on the experimental results, this study explores possible approaches to modeling the size effects on the bending-fatigue life of bulk metallic glasses, and proposes two fatigue-life models based on the Weibull distribution. The first model assumes, empirically, log-linear effects of the sample thickness on the Weibull parameters. The second model incorporates the mechanistic knowledge of the fatigue behavior of metallic glasses, and assumes that the shear-band density, instead of the flaw density, has significant influence on the bending fatigue-life cycles. Promising predictive results provide evidence of the potential validity of the models and their assumptions.

Keywords: Bulk metallic glasses; Bending test; Fatigue-life modeling; Weibull distribution

1. Introduction

Bulk metallic glasses (BMGs) have attracted extensive interest over the last two decades because of their unique properties, such as good corrosion resistance, superior elastic limits, high strengths and low coefficients of friction [1,2]. There have been extensive studies concerning size effects on ductility and strength of BMGs [3–19]. However, little research has been done concerning size effects on fatigue behavior of BMGs. Especially, size effects on fatigue-life distributions have not been well investigated. This study attempts to model size effects on the bending-fatigue life of BMGs based on the fatigue-life data of $Zr_{50}Cu_{30}Al_{10}Ni_{10}$ (in at.%) BMG samples of two different thicknesses, 2 and 3 mm. Experimental results indicated that, under the same bending-stress condition, large samples tend to have longer fatigue lives than small samples [6]. Two statistical fatigue-life models based on the empirical assumptions and mechanistic understanding of the fatigue mechanism, respectively, are proposed and compared in this study.

It has been widely observed that thin wires or films of metallic glasses can be bent plastically while thick plates of metallic glasses fracture upon bending [4,20]. This size effect on bend ductility of metallic glasses has been investigated in terms of the shear-band formation, shear-band spacing and shear-band offset [4,5]. By bending $Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$ (at.%) BMG samples of varying thickness, Conner et al. [4] found that the shear-band spacing scales linearly with the sample thickness, and that the shear-band offset at a given curvature increases as the square of the sample thickness. Deformation in BMGs is accommodated through the generation of multiple shear

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bands, which improve the ductility of BMGs, especially when the sample size becomes smaller [4,5].

A recent experimental study investigated the size effects on the fatigue behavior of Zr-based BMGs with different sizes under four-point-bending fatigue loading [6]. One interesting finding was that BMG samples with a large size tend to have longer fatigue lifetimes and higher endurance limits than those samples with a small size under four-point-bend loading [6]. During the experiments, small-sized BMG samples exhibited flexural and fracture failure modes, while large-sized BMG samples only showed a fracture-failure mode. This trend may be attributed to the improved bend ductility of the small-sized BMG samples. Multiple shear bands and, thus, cracks in the small-sized BMG samples can form easily during bending-fatigue experiments due to the improved bend ductility. A small-sized BMG sample gradually degrades its flexure strength when these shear bands form. Moreover, that study confirmed that the shear-band spacing scales linearly with the sample thickness regardless of metallic glasses and test loading (i.e., monotonic bending or cyclic bending) [6].

Modeling the size effects on the fatigue life of BMGs under bending, however, has not been adequately investigated. When the fatigue failure of a brittle material is governed by the flaws, Weibull statistics is the most popular mathematical description for the fatigue life, time to failure or strength of the material [21,22]. Weibull statistics assume that the probability of finding critical flaws is proportional to the volume of the material tested if the failure is controlled by volume flaws, or to the surface area if the failure is controlled by surface flaws, resulting in the volume-flaw-based Weibull distribution and the surface-flaw-based Weibull distribution given by

$$F(N|\beta_V,\theta_V) = 1 - \exp\left(-V^*\left(\frac{N}{\theta_V}\right)^{\beta_V}\right), \quad (1)$$

and

$$F(N|\beta_S,\theta_S) = 1 - \exp\left(-S^*\left(\frac{N}{\theta_S}\right)^{\beta_S}\right), \quad (2)$$

respectively, where N denotes the fatigue life (cycles to failure), F is the cumulative distribution function of the fatigue-life distribution, θ and β are, respectively, the scale parameter and the shape parameter of the Weibull distribution and V^* and S^* are the effective volume and the effective surface, respectively [10]. The two flaw-based Weibull distributions have been widely used to characterize the lifetime (or strength) distribution and the lifetime (or strength) dependence on sample size for a variety of different materials, such as the strength of $Zr_{35}Ti_{30}Co_6Be_{29}$ metallic-glass nano-pillars under uniaxial compression tests [7]. The failure of BMGs under bending, however, is largely controlled by the shear-band processes [6], and the Weibull statistics cannot adequately describe the dependence of the bending-fatigue life of BMGs on the sample size. New statistical fatigue-life models that effectively consider the size dependence of the bending-fatigue life are, therefore, proposed in this study.

2. Experimental method

The ladle-hearth type arc-melt tilt-casting technique was employed to manufacture $Zr_{50}Cu_{30}Al_{10}Ni_{10}$ (at.%) BMG samples. The master-alloy ingots were first produced by arc-melting mixtures of pure Zr, Cu, Al and Ni metals in an argon atmosphere. A special Zr-crystal rod (<0.05 at.% oxygen) was used to form the master-alloy ingots in order to reduce the oxygen concentration of the alloys [2,6]. Finally, the rod BMG ingots were fabricated with a diameter of 6 mm. Then, the rod BMG ingots were cut into rectangular beam samples with the dimension of 3 mm × 3 mm × 25 mm for large samples and 2 mm × 2 mm × 25 mm for small samples to carry out bending-fatigue experiments. All samples were carefully polished to avoid surface effects before fatigue testing [6].

A computer-automated servohydraulic-testing equipment was utilized to run fatigue experiments. The fatigue specimens were cyclically loaded at various stress ranges with an R ratio ($R = \sigma_{min}/\sigma_{max}$, where σ_{min} and σ_{max} are the applied minimum and maximum stresses, respectively) of 0.1 with a load-control mode. A sinusoidal waveform was employed at a frequency of 10 Hz. Fatigue stress-cycles data were obtained from the four-point-bending setup with an inner span of 10 mm and an outer span of 20 mm [6]. The maximum applied stress vs. the number of fatigue cycles to failure results (S–N curves) were developed for both large (3 mm × 3 mm × 25 mm) and small (2 mm × 2 mm × 25 mm) samples.

3. Models

This study first establishes a general statistical framework for modeling the S–N behavior of BMGs. S–N data of BMGs have been reported in many experimental studies [6,23–25]. The fatigue-life modeling, however, has not been adequately studied [26]. Existing models and methods for analyzing the fatigue-life data, such as the American Society for Testing and Materials (ASTM) Standard E739 [27], are inadequate.

A commonly used analytical representation of the S–N curves, considering the fatigue-endurance limit, is given by [28]

$$N = \begin{cases} c(S-S_0)^{-d}, & S > S_0, \\ \infty, & S \le S_0, \end{cases} \quad (3)$$

where N, S and S_0, are, respectively, the cycles to failure, the applied stress and the fatigue-endurance limit, and c and d are positive material parameters. Taking the natural logarithm on Eq. (3) results in

$$\log(N) = \begin{cases} \gamma_0 + \gamma_1 \log(S-S_0), & S > S_0, \\ \infty, & S \leqslant S_0, \end{cases} \quad (4)$$