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An approach to modeling the *S–N* behavior of bulk-metallic glasses

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Abstract

Probability and statistics analyses are increasingly being used for reliability and durability assessments for life predictions of advanced material systems. Fatigue-life predictions have historically been based on crack-growth approaches, which are almost exclusively empirically based. Consequently, they often do not adequately reflect long-term operating conditions, which are well beyond laboratory test conditions. These models usually fail to identify the sources of the randomness and the extent of their contributions to the total variability. Using a simple crack-growth model, the variability inherent in the stress vs. fatigue-life (*S–N*) response for bulk-metallic glasses (BMGs) can be related to some of the key random variables that are readily identified in the models. The identification and quantification of these variables are paramount for predicting fatigue lives and reaching some understanding of the fundamental damage growth mechanisms in BMGs. The effectiveness of the modeling is shown through the analyses of a set of *S–N* data for BMGs where the variability associated with the material chemistry and structure and specimen preparation is considered.

Keywords: Metallic glasses; High cycle fatigue; Scanning electron microscopy (SEM); Probability and statistics modeling

1. Introduction

Interest in bulk-metallic glasses (BMGs) has grown considerably in recent years [1–4]. This interest is motivated by a relatively low elastic modulus and high strength. The fatigue-life, however, has not been adequately studied to date, especially when the variability is considered. Crystal defects (e.g., dislocations and grain boundaries) are not present in BMGs, and the real nature of the deformation mechanisms in BMGs still remains unclear. For structural applications, fatigue behavior is critically important for life predictions and failure analyses. Nevertheless, the fatigue study of BMGs is very limited [5–13]. In this paper, the fatigue characteristics of BMGs are modeled by a simple fatigue crack-growth model. Since materials degradation is a principal cause for the reduction in reliable life predictions, a suitable model is essential for these non-traditional materials. Likewise, the model should incorporate the inherent variability in the materials. Using classical crack-growth modeling, the observed variability in the stress vs. fatigue-life cycles (*S–N*) response for BMGs will be related to certain random variables (rvs) in the model. The effectiveness of the modeling is shown through the analysis of a conglomerate set of *S–N* data for BMGs. The variability associated with the material chemistry and structure and specimen preparation is considered. The purpose of this paper is to suggest an approach for life prediction of BMGs.

2. *S–N* data

The fatigue-life data in Refs. [5–9] has been augmented in order to develop an exploratory *S–N* database that includes a variety of test conditions as well as metallic

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glasses. In all, about 50 BMG specimens have been tested for the following BMGs: $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$, $Zr_{50}Cu_{40}Al_{10}$, $Zr_{50}Cu_{30}Ni_{10}Al_{10}$ and $Zr_{52.5}Al_{10}Ti_5Cu1_{7.9}Ni_{14.6}$. The details of the specimen preparation and testing conditions are given in Refs. [5–9]. Fig. 1 shows the conglomerate data plotted in the traditional *S–N* format. Several observations are in order. The characteristic *S–N* curve for fatigue data is usually determined from the data medians or averages for a single type of material. However, the amount of data for each specific type of BMG, shown in Fig. 1, is insufficient to statistically model the fatigue-life adequately. Consequently, for the analyses herein, it is assumed that the data from all of the different BMGs can be considered to be sufficiently similar that their difference is within suitable statistical accuracy, i.e. all of the data behave as if they had been taken from similar BMGs. Fortunately, all of the specimens were tested in the same laboratory so that the environment and test conditions are nominally identical. Thus, some of the experimental error is reduced. As the stress amplitude is reduced, it is apparent that the scatter in the *S–N* data increases, which is common for the fatigue-life. This trend may be partially due to different damage mechanisms that are operative for applied stresses in the normal range of operation. For instance, Fig. 2 shows two different specimen failures in which failure initiated at different locations. For the $Zr_{50}Al_{10}Cu_{30}Ni_{10}$ on the left, the damage initiated at the surface, induced by some external damage, but for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ specimen on the right, the damage initiated from an internal damage site. These initiation locations could be due to the local inhomogeneities, specimen preparations or material irregularities that occur in a high-stress region. Further characterization of these initiation sites would make a significant contribution to advancing the modeling. In fact, for other materials, it has been shown that the damage initiation at external vs. internal locations has a significant impact on the fatigue-life [14]. The goal herein is to propose a simple model for the fatigue-crack-growth behavior, based on classical analyses for the damage evolution in BMGs.

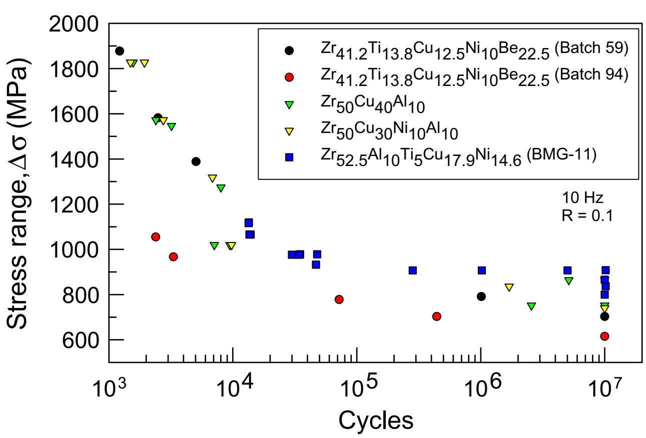

Fig. 1. *S–N* data for the BMG specimens.

To display the scatter in the data, given an applied stress range, $\Delta\sigma$ ($\Delta\sigma = \sigma_{\min} - \sigma_{\max}$, where $\sigma_{\min}$ and $\sigma_{\max}$ are the applied minimum and maximum stresses, respectively), Fig. 3 shows the fatigue data plotted on a Weibull probability paper for the values of $\Delta\sigma$ from at least three observations. This paper was chosen primarily for convenience, but if the data can be adequately represented by a linear curve, then a two-parameter Weibull cumulative distribution function (cdf) is an acceptable empirical statistical model. The data for all values of $\Delta\sigma$ appear to be reasonably linear, thus a two-parameter Weibull cdf would be an acceptable statistical characterization of the data. This trend is especially true for $\Delta\sigma$ greater than 1000 MPa;

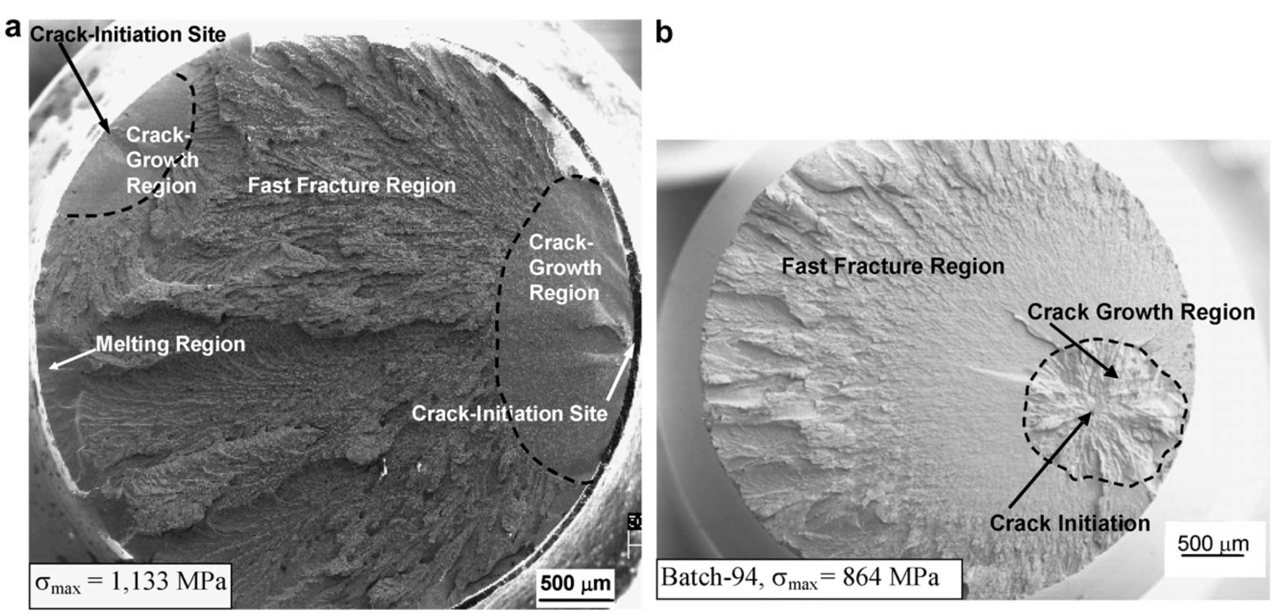

Fig. 2. Fracture surfaces of representative specimens of (a) $Zr_{50}Al_{10}Cu_{30}Ni_{10}$ and (b) $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$.