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Fatigue damage of closed-cell aluminum alloy foam: Modeling and mechanisms

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ABSTRACT

The objective of this work is to experimentally investigate the damage evolution and damage mechanism in closed-cell aluminum alloy foam under tension–tension fatigue loading. Constant amplitude fatigue tests are performed for the aluminum alloy foam, and experimental results indicate the large scatter of the fatigue damage in the aluminum alloy foam. To describe the fatigue damage with large scatter, a statistical fatigue damage model is developed on the basis of continuum damage mechanics. It is seen that the statistical damage model can describe the fatigue damage of the foam. Scanning electron microscopy (SEM) observation on the fracture surface of the tested specimen is carried out to understand the damage mechanisms of the foam. Four major categories of fatigue damage mechanism are concluded, i.e. damage initiates from the material surface, damage initiates on the cell wall, damage initiates at the intersection of several cell walls and damage initiates from the edge of cell. The high-resolution SEM images reveal that the fatigue mechanisms of the foam are mainly governed by the cell structure.

1. Introduction

In the last decades, metal foam has been widely used in a number of engineering structures, such as automobile, aircraft, and spacecraft, and attentions have been devoted to the plasticity, dynamic response and energy absorption of metal foam [1–4]. However, there are relatively few investigations on foam fatigue. Previous studies show the large scatter characteristic of the foam fatigue [5–15]. Based on the tension–compression fatigue experimental results of two kinds of metal foams, Zettl et al. [6] demonstrated a pronounced scatter in the lifetimes of the foams. McCullough et al. [7] performed tension–tension fatigue and compression-compression fatigue of closed-cell aluminum alloy foams. Through compression-compression fatigue experiments, Kolluri et al. [8] investigated the mechanical behavior of foam under lateral constant. In both cases, it was found that the fatigue of foams is highly sensitive to the applied stress. Zenkert and Burman [9] compared the tensile, compressive and shear fatigue testing of closed-cell foam with different densities, and found that different load types exhibit different failure mechanisms. Kanny et al. [10] conducted flexural fatigue tests on cross-linked PVC foams over a wide range of density. It was shown that the flexural fatigue strength of the foams increased as the density increased. Significant scatter of the fatigue properties was also reported for open cell aluminum foams [13]. The larger scatter characteristic of fatigue property makes it difficult to study the fatigue behavior of foam materials.

Previously, various methods were adopted to study the fatigue behavior of materials. Among them, the continuum damage mechanics (CDM) was most commonly used in the framework of continuum mechanics and continuum thermodynamics [16–20]. CDM gives a better understanding of the state of materials by the definition of one or several continuum damage variables representing the material degradation. In all these studies major emphasis was put on the development and application of deterministic damage models. However, in their current form, these deterministic damage models are valid only for predicting fatigue properties of materials without large scatter [18,20].

Existing literature shows that the structure is a key factor leading to the scatter of mechanical properties of foams [21–27]. Ramamurty and Paul [21] experimentally studied the variability in the elastic modulus, plastic strength, and energy absorption of a closed-cell Al foam. By considering the micro-mechanism of deformation in the closed-cell foam they related the variability of mechanical properties to the variance in the cell-size. Zhu and Windle [22] found that compared to regular foam highly irregular foam has a lower effective stress at high compressive strains. The

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experiments performed by Kolluri et al. [8] and Simon and Gibson [23] illustrated that the defect distribution and orientation with respect to the loading directions have major impact on the scatter of mechanical properties of metal foams. Brothers and Dunand [24] found that the pore size has significant effect on the flow stress. The influences of inhomogeneous micro-structure on stress distribution and fracture of cell walls had been studied by Andrews et al. [25]. Our recent work on the fatigue of closed-cell aluminum alloy foam showed that the fatigue life decreases as the number and the size of large cell increase [26]. Scanning electron microscopy (SEM) studies were performed to examine the dependence of lifetime on the inhomogeneous structure of the foams [5,6]. While there have been some progress in the study of fatigue damage of metal foams, understanding of the dependence of fatigue property variability on the structure characteristics of foam is still very limited [27].

In this paper, the damage evolution and damage mechanisms in closed-cell aluminum foam material are investigated. The paper is organized as follows. Experimental details are presented in Section 2. The statistical fatigue damage model is derived in Section 3, and analysis of the fatigue damage mechanisms is presented in Section 4. Finally, concluding remarks are summarized in Section 5.

2. Experimental

2.1. Material and specimens

The closed-cell aluminum alloy foam examined in this study was provided by the Material Institute of Luoyang, China. The foam has an average relative density ρ of 28.7%. Dog-bone shape specimens were used for both static and fatigue tests. The dimensions of specimen are shown in Fig. 1, in which the black frame indicates the gauge section of 50 mm × 20 mm × 20 mm. Static properties of the foam were tested at room temperature by using the universal MTS 880 machine. Three specimens were tested at a crosshead speed of 2 mm/min. An extensometer was used to monitor the strain within the gauge section. The load and strain were recorded by using a computer data-acquisition system. The average value of tensile strength is 9.27 MPa. Details on the material and its static properties can be found in a previous study [26].

2.2. Fatigue tests

Due to the fact that no fatigue test standard is available for foam material, we referred to the ASTM standard (ASTM E466-07) herein for the fatigue tests of foam material. The universal MTS 880 machine was employed to carry out the tension–tension fatigue tests. Constant amplitude fatigue loads with a sinusoidal waveform and a stress ratio $R = 0.1$ ($R = \sigma_{min}/\sigma_{max}$ with σ_{min} and σ_{max} being the minimum and maximum stresses in one load cycle) were applied. The loading frequency was 20 Hz. Four stress levels with maximum tensile stresses of 7 MPa, 6.5 MPa, 6 MPa and 5.5 MPa, respectively, were considered and a total of 13 dog-bone shape specimens shown in Fig. 1 were tested. An extensometer was used to monitor the strain within the gauge section. The load and strain were continuously recorded by using the computer data-acquisition system. All the fatigue tests were conducted at room temperature.

It should be noted that due to the relatively low compression performance of foam the specimens could be easily destroyed by the testing machine. Thus, the specimens could not be directly fixed to the testing machine. In this study, loading fixtures were specially designed, as shown in Fig. 2, in which the specimen was indicated by the cellular pattern and the fixtures were daubed on gray color. The specimen was firstly bonded to the fixtures and then the fixtures were connected to MTS hydraulic grips.

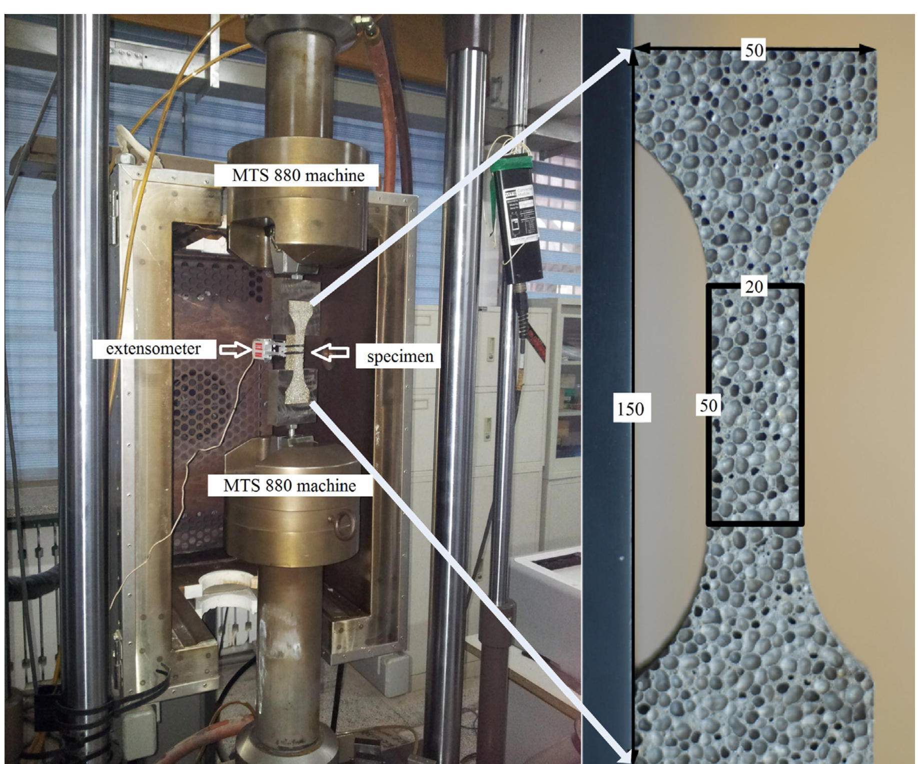

Fig. 1. Dimensions of the closed-cell aluminum foam specimen (mm).