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Effect of the large cells on the fatigue properties of closed-cell aluminum alloy foam

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ABSTRACT

The effect of the large cells on the fatigue properties of closed-cell aluminum alloy foam is studied experimentally and numerically. To do this, a parameter termed as characteristic diameter (D_{ch}) is introduced. 44 dog-bone type specimens are tested with MTS fatigue test machine. In addition, the fatigue performances are numerically simulated by using foam models generated with a program given in this paper. In both cases, large scatter in fatigue life is observed. After classifying the foams into different groups based on their D_{ch}, the fatigue life results of foams within the same D_{ch} range show smaller diversity. It indicates that D_{ch} is an effective parameter which can be used to classify the fatigue performance of foam materials. For foams with same relative density, foams with higher D_{ch} are inclined to have shorter fatigue lives, even though the cell size distributions of foams are different. It is concluded that the fatigue life of foam is dominated by the large cells rather than the cell size distribution. By observing the fatigue life contour obtained from numerical simulation, the dangerous regions in the cell structure are found near the cell walls of larger cells and on the outer surfaces of foam.

1. Introduction

Foam materials have a wide range of applications in the aerospace, automotive, and biomedical industries. In the last two decades, a large number of researches have been performed on the deformation, fracture, plasticity, dynamic response and energy absorption of cellular foams experimentally [1–12] and numerically [13–22], while relatively few studies have been conducted on the fatigue of foam materials [23–32]. As the development of foam materials, the components made of metallic foam are applied in the load-bearing structures extensively. Some of them are subjected to cyclic loading in practical applications. For example, the helicopter components made of aluminum foams are exposed to fluctuating strains under operating conditions [23]. The knowledge of fatigue and fracture mechanism is essential for the design and usage of foam-containing structures. Zettl et al. [24] demonstrated a pronounced diversity in fatigue life of foams in the tension-compression fatigue test on Al-Mg-Si foam and Al-Si foam. McCullough et al. [25] investigated the fatigue behavior of Alulight closed-cell aluminum alloy foams and observed the scatter of fatigue life in both tension-tension and compression-compression loading conditions. Recently, Zhao et al. [26,27] conducted tension-tension fatigue tests on closed-cell aluminum alloy foams and developed a statistical model to characterize the large scatter in fatigue life and fatigue damage. However, the evaluation of fatigue performance given by *P-S-N* curves is conservative. The foams with better fatigue performance might be underestimated in the engineering design. In addition, the observation of fracture surfaces showed that the scatter in fatigue performance was related to the inner different cell structures of foam materials.

According to the preview studies [33–42] on the cell structure of foam materials, it was shown that the cell structure has a significant influence on the mechanical properties of foams. Beals et al. [33] studied the compressive properties of aluminum foam including density gradient. The results indicated that the energy absorption efficiency of foam decreases with an increasing variation in the density. Based on the results of FEM simulations, Zhu et al. [34,35] demonstrated that the elastic and plastic performances of foams were related with the irregularity of cell structure for open-cell foams. Bekoz et al. [36] experimentally investigated the low alloy steel foams with different pore sizes and porosities which were produced through the powder metallurgy, and found the larger pore size caused a bigger stress drop ratio under uniaxial compression within the range of investigated porosities. Chen et al. [37] applied the Laguerre tessellations to model the closed-cell M130 foam and concluded that both the cell size variation and cell wall thickness variation impaired the elastic properties of foams. However,

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the study on the relation between the cell structure and fatigue behavior of foam materials is relatively few [23,26,28]. Thus, it is essential to investigate the effect of the inner cell structure on the fatigue behavior of foam materials.

In this study, the relation between the large cells in the cell structures and the fatigue performance of aluminum foams is investigated. The organization of this paper is as follow. The structural parameter used for describing the fraction of large cells in cell structure is introduced in Section 2. Experimental results are presented and discussed in Section 3. FEM modeling and numerical fatigue simulation are presented in Section 4.1 and Section 4.2. Quantitative analysis on the factors that influence the fatigue performance of foam materials is proposed in Section 4.3. Related discussions on the cell structure are reported in Section 5. Finally, concluding remarks are summarized in Section 6.

2. Definition of characteristic diameter

Previous researches [26,27] showed that the foam possessing large pores inside is inclined to have a short fatigue life. In this study, characteristic diameter D_{ch} is defined to describe the fraction of large cells in foam materials. As shown in Fig. 1, cross section of foam materials is composed of cells and cell walls. The gross cell area S_t is defined as the summation of the area of all cells located on the cross sections, which is written in Eq. (1):

$$S_t = \sum_{i=1}^{n} S_i \tag{1}$$

where n is the total number of cells located on the cross sections and S_i is the section area of cell i.

Since the tiny cells on the sections of foams are difficult to measure in practical, the gross cell area S_t can also be given reasonably by Eq. (2):

$$S_t = S_0\cdot(1-\overline{\rho}) \tag{2}$$

where S_0 is the area of the cross sections which are selected to evaluate the cell structure of foam material, and $\overline{\rho}$ is the relative density of aluminum foam. Herein, the relative density of foam is used as a substitute for the relative surface density of cross section. By measuring the geometric parameters of FEM models given in Section 4.1, it is shown that $\overline{\rho}$ is almost equal to the relative surface density of cross section for foams with different cell structures.

The gross area of the cells whose diameters are smaller than d is defined as S_d.

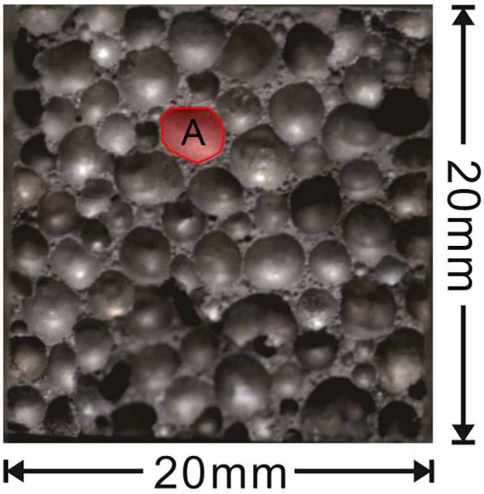

Fig. 1. Cross section of closed-cell aluminum foam used in this study.

$$S_d = S_t - \sum_{i=1}^{m} S_i \tag{3}$$

where m is the total number of cells whose diameters are larger than d.

The cumulative area fraction F for cells whose diameters are smaller than d is given in Eq. (4):

$$F(d) = \frac{S_d}{S_t} \tag{4}$$

Therefore, 1-F represents the proportion of the total area of cells whose diameters are larger than d, which can be used to describe the fraction of large cells in the foam materials. To classify the foam materials with different cell structures, characteristic diameter D_{ch} is defined as the diameter which is corresponding to 1-F of 0.2.

3. Fatigue experiment of closed-cell aluminum foam

The tension-tension fatigue tests of closed-cell aluminum alloy foams were carried out on a universal MTS 880 machine in the previous work [26,27]. As shown in Fig. 2, the dog-bone shape specimen with a thickness of 20 mm was fixed on the test machine with specially designed fixtures. The cross section area of specimen is 20 mm × 20 mm. Constant amplitude fatigue load with a sinusoidal waveform was applied on the specimen at a frequency of 20 Hz. The stress ratio R defined as the ratio of the minimum stress $\sigma_{\min}$ to the maximum stress $\sigma_{\max}$ in one load cycle ($R = \sigma_{\min}/\sigma_{\max}$) was set to be 0.1. A total of 44 dog-bone shape specimens were tested at five stress levels with the maximum tensile stresses $\sigma_{\max}$ of 5.5 MPa, 6 MPa, 6.5 MPa, 7 MPa and 7.5 MPa. The corresponding maximum load $P_{\max}$ and minimum loads $P_{\min}$ are listed in Table 1 for different stress levels.

Fig. 3 shows the tension-tension fatigue test results of the aluminum foam. It is observed that the fatigue life has a large diversity at the same stress level.

As shown in Fig. 1, the fracture surface of foam specimen was used to characterize the inner cell structures of foam specimens, because the fracture surface of specimen might be more reasonable to reflect the effect of inner cell structures on the fatigue behaviors of foam specimen. The area of the individual cell (for example, A in Fig. 1) was obtained by using picture processing software Image-Pro Plus. The magnification factor (mm/pixel) of picture was obtained by the calibration scale (20 mm × 20 mm as shown in Fig. 1). The diameters of cells on the fracture surface were then calculated and classified in several diameter ranges for each specimen. The numbers of cells in different diameter ranges for specimens tested at 5.5 MPa are shown in Table 2.

According to the data in Table 2, the fractions of area occupied by different cell diameter ranges are calculated and listed in Table 3.

Based on the data listed in Table 3, a series of cumulative area fractions F for specimens tested at the stress level of 5.5 MPa are obtained and shown in Fig. 4. The cumulative area fractions are fitted with the Weibull cumulative distribution function (CDF) for each specimen. The distribution parameters (λ and k) of Weibull distribution are thus obtained:

$$F(d;\lambda,k) = 1-\exp\left[-\left(\frac{d}{\lambda}\right)^k\right] \tag{5}$$

where d is the cell diameter, $\lambda > 0$ is the scale parameter and $k > 0$ is the shape parameter. In order to give a reasonable description of the distribution of cell diameters and to consider the potential larger cells that do not appear on the fracture surface, the cumulative area fraction F corresponding to the cell diameter of 4.3 mm, which is the diameter of the largest cell observed in the sections of all specimens, is set to be 0.9999. The fitting curves are also shown in Fig. 4 for each specimen. With the distributions shown in Fig. 4, the D_{ch} of the specimens tested at 5.5 MPa can be given and listed in Table 4. Similarly, the characteristic diameter D_{ch} of other specimens tested at the stress levels of 5 MPa,

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