Materials Letters 160 (2015) 68–71

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

Experimental investigation of the fatigue of closed-cell aluminum alloy foam

M.D. Zhao, Xueling Fan*, Qin-Zhi Fang, T.J. Wang*

State Key Laboratory for Strength and Vibration of Mechanical Structures, Department of Engineering Mechanics, School of Aerospace Engineering, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form
7 July 2015
Accepted 8 July 2015
Available online 9 July 2015

Keywords:
Fatigue
Porous materials
S–N curves
Statistical analysis
Metal foam

ABSTRACT

Tension–tension fatigue tests are carried out to investigate the fatigue of closed-cell aluminum alloy foam. The stress–life (*S–N*) curve of the foam is obtained, in which large scatter is observed and discussed in detail. To understand the scatter of fatigue life of the foam, fracture surface is examined. The fatigue life decreases as the number and the size of large cells increase. The irregularity of inner cell structure of the foam attributes to the scatter of fatigue life. Then, a statistical stress–life model is developed, and a series of statistical probability–stress–life (*P–S–N*) curves are obtained. The *P–S–N* curve is efficient in describing the fatigue of foam materials.

1. Introduction

Metal foam has been widely used in a number of engineering structures, such as vehicles, aircrafts, spacecrafts, etc. In the last two decades, attentions have been devoted to the plasticity, dynamic response and energy absorption of metal foam materials and structures [1–4]. It is well known that fatigue is a major failure mechanism of materials and structures [5]. So the understanding of fatigue behavior is of particular importance in practical application of metal foam. However, both the property of parent material and the own structure of foams affect the mechanical performance of metal foams. The inhomogeneous microstructure results in the large scatter in mechanical properties of the metal foams [6]. For example, large scatter of fatigue life is observed for foam materials under tension–tension [7], tension–compression [8], compression–compression [9], shear [10] and flexural [11] fatigue loading, etc. So it is difficult to use the traditional *S–N* equation [12] to describe the scatter characteristics of the fatigue life of foams, and statistical analysis is needed [13,14].

The challenge in understanding of the fatigue behavior of metal foams is twofold: (1) the properties of foam test samples can be influenced by the state of the surface and the way in which the specimen is gripped and loaded, and (2) the properties of foam test samples depend on the ratio of the specimen size to the cell size, so the specimens must be large (at least seven cell diameters of every dimension) [6]. As a result, up to now, very limited works have been conducted on the fatigue of foam materials [15,16]. This motives us to experimentally investigate the fatigue of closed-cell aluminum alloy foams. The *S–N* curve of the foam is experimentally obtained and the effect of irregularity of inner cell structure is discussed. Finally, a statistical *S–N* law is established to describe the probabilistic fatigue life of foam materials.

2. Experimental

The closed-cell aluminum alloy foam tested herein is provided by the Material Institute of Luoyang, China. The average relative density ρ of the foam, which is defined as the ratio of foam density to that of parent material, is 28.7%. Using the universal MTS 880 machine, three dog-bone shape specimens were tested to measure the Young's modulus and the strength of the foam according to ASTM E111-97. The specimens were manufactured by using wire-electrode cutting machine. The dimensions of specimen were shown in Fig. 1, in which the gauge section is of 50 mm × 20 mm and the thickness is 20 mm. To avoid destroying the foam specimen, specified fixtures were designed, as shown in Fig. 1. The crosshead speed was 2 mm/min and an extensometer was used to monitor the strain in the gauge section. The load and the strain were recorded by using a computer data-acquisition system. The

---

* Corresponding authors. Fax: +86 29 82669044.
E-mail addresses: fanxueling@mail.xjtu.edu.cn (X. Fan), wangtj@mail.xjtu.edu.cn (T.J. Wang).

http://dx.doi.org/10.1016/j.matlet.2015.07.040
0167-577X/© 2015 Elsevier B.V. All rights reserved.

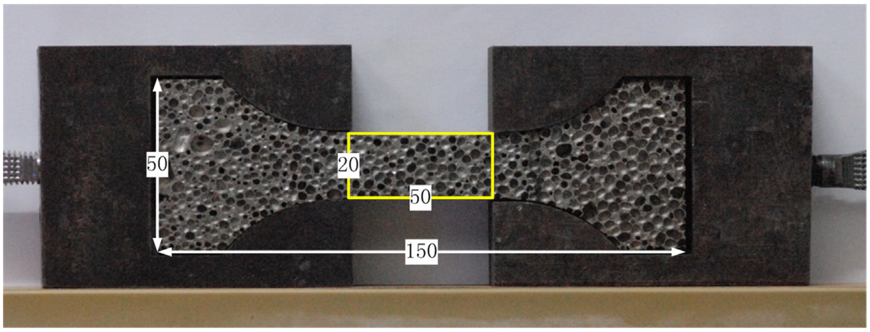

Fig. 1. The specimen with dimensions and the specially designed fixtures (mm).

obtained average values of tensile elastic modulus and strength of the foam were 479 MPa and 9.27 MPa, respectively.

The universal MTS 880 machine was employed to carry out the tensile fatigue tests on the basis of ASTM E466-96 due to no available fatigue test standard for foams. The same dog-bone shape specimens (Fig. 1) were used for the fatigue tests under constant amplitude loading with a sinusoidal waveform. According to Ref. [6], the fatigue of aluminum alloy is insensitive to the loading frequency. Thus, to reduce the test time we choose the highest frequency (20 Hz) of the test machine. The stress ratio ($R = S_{min}/S_{max}$) was set to be 0.1, which was commonly used in previous studies, where S_{min} and S_{max} were the minimum and maximum stresses in one load cycle. Five stress levels with maximum tensile stresses of 7.5 MPa, 7 MPa, 6.5 MPa, 6 MPa, and 5.5 MPa were considered. A total of 46 specimens were tested at room temperature. To examine the effect of cell structure on the fatigue life of the foam, the fracture surface was observed by using a digital camera (Nikon D200).

3. Results and discussions

The fatigue lives of the foam specimens are shown in Fig. 2 for each loading level. An obvious decrease in fatigue life is observed with the increasing of loading level. At each fatigue loading level, large scatter is the main feature of the fatigue life of foam. The highest fatigue life can be several hundred times larger than the lowest value. For example, the fatigue lives fall in the range from 2.6×10^2 to 3.2×10^4 at the stress level of 6 MPa.

Fig. 3 shows the fracture surfaces of six specimens respectively tested at the stress levels of 7.5 MPa and 5.5 MPa, in which A and B represent loading levels, while 1, 2 and 3 represent different specimens, see Fig. 2 for reference. Remarkable differences exist among the inner cell structures of different specimens. A relatively uniform cell structure is observed in Fig. 3(A3), which leads to relatively uniform stress distribution and low stress concentration and thus long fatigue life. In contrast, the irregular cell structure shown in Fig. 3(A1) leads to large stress intensity and results in relatively short fatigue life. Above observations confirm that the fatigue life depends significantly on the inner cell structure of foams.

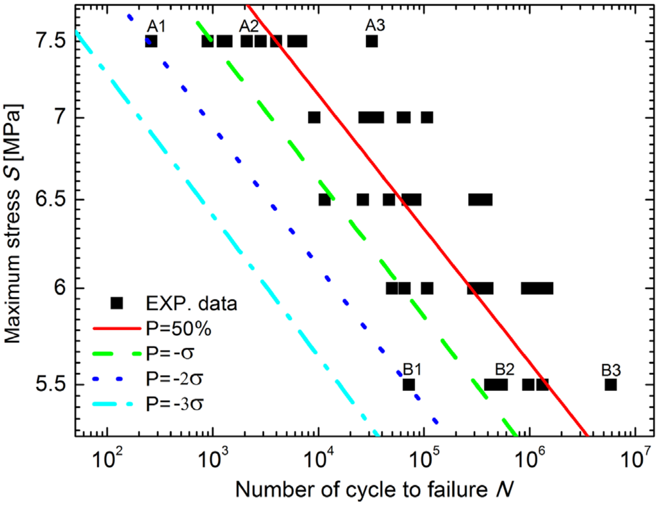

Fig. 2. Experimental *S–N* and predicted *P–S–N* curves for different failure probabilities.

The diameters of cells are measured from the fracture surfaces shown in Fig. 3. Then, the ratio of the total area of large cells (the diameter is larger than 3 mm) to the cross sectional area, P_r, is obtained. Among the specimens tested at 7.5 MPa, specimen A3, which gives the longest fatigue life, has the minimum ratio P_r of 0%. In contrast, specimen A1, which gives the shortest fatigue life, has the maximum ratio P_r (23.7%). For specimen A2, which gives an intermediate fatigue life, the P_r value (11.5%) lies between those of specimens A1 and A3. The increase of cell size decreases the fatigue life of foam.

The fracture surfaces of specimens tested at stress level of 5.5 MPa and marked with B1–B3 in Fig. 2 are shown in Fig. 3(B1)–(B3), and the corresponding P_r values are 16.2%, 7.5% and 2.3%, respectively. Similar conclusions can be drawn from the analysis of the cell structures and the fatigue lives. Uniform cell structure and low P_r value result in long fatigue life. Similar trends are observed for other load levels.

The phenomenon is mainly caused by the inhomogeneous stress distribution in the foam material. Obviously, under the same load condition the stress level is higher on a large-size cell wall. So the specimen with large cells is prone to crack initiation than those of with small cells. With cycle loading increases, the relatively large stress will make the crack propagation is more quickly for the specimen with large cells. So the fatigue life of specimen with larger cells is shorter than those with small cells. The increase of cell size decreases the fatigue life of foam materials.

4. Statistical analysis

The stress–lifetime relationship of the foam can be described by [12]

$$S^m N = C \tag{1}$$

where N is the fatigue life, S is the maximum stress, C and m are material constants. Based on the experimental data plotted in Fig. 2, we obtained $C = 11.803$ and $m = 0.054$.

However, Eq. (1) could not describe the scatter of fatigue life. Herein, the logarithmic normal distribution is adopted to characterize the distribution of fatigue life. The probability density