Materials Science & Engineering A 708 (2017) 424–431

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Experimental investigation of the fatigue crack propagation in a closed-cell aluminum alloy foam

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ARTICLE INFO

Keywords:
Aluminum alloy foam
Fatigue crack propagation
Statistical mechanics
SEM observation

ABSTRACT

Fatigue crack propagation in a closed-cell aluminum alloy foam is experimentally investigated in this work. A series of fatigue tests are conducted to obtain the *a-N* curves (i.e. crack length vs loading cycle number) and d*a*/d*N*-ΔK curves (fatigue crack propagation rate vs stress intensity). Statistical analysis is carried out to assess the stochastic and scattering characteristics in the fatigue crack propagation of the foam, based on which a statistical fatigue crack propagation model is developed. Furthermore, the fracture surfaces of the foam specimens are characterized, as well as the fatigue fracture morphologies. It is demonstrated that the structural heterogeneity inherent in the material and the difference in the cell structures between different specimens account for the great scatter of the fatigue crack propagation in the close-cell aluminum alloy foam.

1. Introduction

Metal foams have been widely used in many engineering structures, such as those in automobile, aircraft and spacecraft [1]. Great efforts have been devoted to studying the mechanical behaviors of metal foams and their constructed sandwich structures, among which plastic yielding, energy absorption and dynamic compressive response have been most extensively studied [2–10]. Fatigue is a major failure mode of materials and structures and affected by many factors such as grain boundaries, porosities and inclusions [11–15]. Fatigue, which is a major failure mode of materials and structures, is another important issue for metal foams [16,17], requiring adequate understanding. Normally, the fatigue crack propagation is particularly concerned in engineering design, since the successful application of foam material relies on a fundamental understanding of their resistance to fatigue crack propagation.

Investigations of the fatigue behavior of foam materials are still limited [18–29], especially for the fatigue crack propagation [30–37]. Zhao et al. [26] experimentally investigated the tension-tension fatigue of a closed-cell aluminum alloy foam, and they obtainted the stress-life (*S-N*) curve and developed a statistical stress-life model. Also, Zhao et al. [27] experimentally investigated the tension-tension damage evolution and damage mechanisms in the closed-cell aluminum alloy foam, in which a statistical fatigue damage model was developed on the basis of continuum damage mechanics [38–40]. Noble and Lilley [30] found that the fatigue crack propagation in polymeric foams can be reasonably described by Paris law. Similarly, Shipsha et al. [32] experimentally studied the mode I fatigue crack propagation in polymeric foams by correlating fatigue crack growth rate to stress intensity range ΔK. Their results show that the stress ratio and mean stress have strong influences on the fatigue crack growth rate and the fatigue threshold value. Olurin et al. [33] investigated the dependence of fatigue crack propagation of aluminum alloy foams on the relative density, mean stress and a single peak overload. They concluded that the fatigue crack growth rate is mainly controlled by the progressive degradation of crack bridging by fatigue failure of the cell edges behind the crack tip. Motz et al. [34] studied the effects of crack closure and bridging on the fatigue crack propagation of foam. They found that the fatigue crack propagation mechanism of closed-cell Al foam is different from that of a stainless steel hollow sphere structure. Using the linear-elastic fracture mechanics and elastic-plastic fracture mechanics, Poapongsakorn and Kanchanomai [35] studied the effect of stress ratio on the fatigue crack growth of closed-cell PVC foam. It was found that the interaction between polymer-chain scission and small scale crack-tip blunting was the main mechanism for cyclic-dependent crack growth, whereas the interaction between polymer-chain pullout and large scale crack-tip blunting dominated fracture process for time-dependent crack growth. Cho et al. [36] investigated the geometry dependence of foam fatigue properties. It was revealed that the existence of hole would accelerate the crack propagation and the crack would be towed into the hole due to the stress concentration. Linul et al. [37] investigated the low cycle fatigue behavior of a class of ductile closed-cell aluminum alloy foams

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http://dx.doi.org/10.1016/j.msea.2017.09.120
Received 24 July 2017; Received in revised form 27 September 2017; Accepted 28 September 2017
Available online 07 October 2017

(Alulight M8). It was found that there were three regions of deformation for the aluminum foams under quasi-static compression tests: a linear elastic region, a plateau region and a densification region. It was observed that the scatter of fatigue life increased as the irregularity of cell structure was higher and that the fatigue life decreased as the number and the size of large cells increased when the fractured surfaces were examined.

Many studies show that the fatigue crack propagation in foams shows large scattering and stochastic characteristics [26,27,34,37]. The scattering and stochastic characteristics in the fatigue crack propagation of foam materials are still an open topic. Meanwhile, the fatigue crack propagation mechanism is another emphasis for the fatigue study of foams. To assess the safe reliability of foam materials, studies focusing on these aspects are required, but very limited relevant works have been performed [35,41].

In this study, fatigue crack propagation tests are performed on a closed-cell aluminum alloy foam and a statistical fatigue crack propagation model is proposed based on statistical analysis. Then, fatigue fracture surfaces and morphologies are characterized. The experimental details are presented in Section 2. Experimental results and statistical analysis are presented in Section 3. Section 4 is devoted to the discussion of the mechanisms of fatigue crack propagation in the closed-cell aluminum alloy foam. Finally, concluding remarks are made in Section 5.

2. Experiment

2.1. Material and specimens

A typical closed-cell aluminum alloy (Luoyang Material Institute, China) is studied herein. The preparation process of closed-cell aluminum alloy foam undergoes four stages: (1) the aluminum alloy powder and foaming agent are firstly evenly mixed; (2) press it into a dense prefabricated embryo under proper pressure; (3) the prefabricated embryo is further processed into a semi-finished product; (4) put it into the steel mold and heated until the temperature close to the melting point, so that the foaming agent decomposes and releases the gas to form bubbles, thus producing closed-cell aluminum foam. Its average relative density ρ is 23.8%. Compact tension (CT) specimens were prepared, and the geometry and dimensions are shown in Fig. 1. The thickness and the width W of the specimens is 20 mm and 50 mm, respectively. The initial crack length is 14.5 mm and the ratio of initial crack length a to specimen width W (a/W) is 0.29. The specimen and the initial crack were both manufactured by using a wire-electrode cutting machine, and the crack tip was sharpened by using a razor blade.

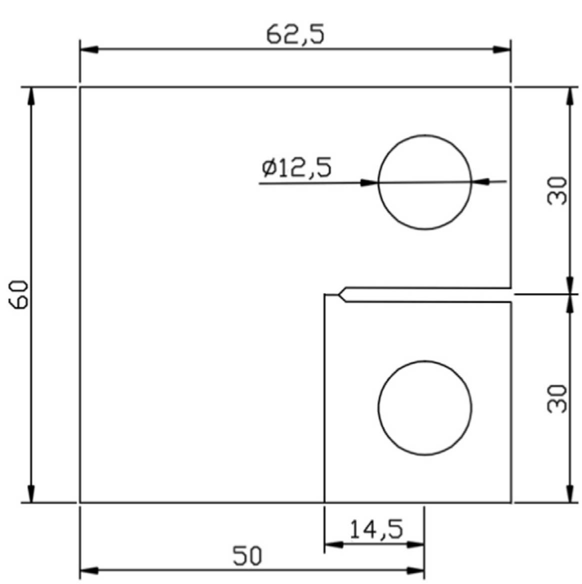

Fig. 1. Compact tension specimen (mm).

2.2. Static and fatigue tests

Static tests were conducted first to obtain the static fracture load, and ASTM E399-09 was adopted herein. Before the tests, the specimens were bonded to specially designed steel clevises through steel tube inserts, and more details can be found in our previous work [26]. Then the clevises were connected to the Instron 5848 testing machine. Five CT specimens were tested under displacement control at a crosshead speed of 2 mm/min. An extensometer was used to monitor the crack opening displacement. The load and the crack opening displacement were continuously recorded by using a computer data-acquisition system. The obtained static fracture load was 414 N, 462 N, 557 N, 589 N and 614 N for five specimens, and the average value was 527.2 N.

After static tests, fatigue crack propagation tests were carried out on fifty specimens by using the same Instron 5848 testing machine. Note that ASTM E647-11 standard was followed herein due to no specific test standard is available for the fatigue crack propagation of foam materials. A constant amplitude fatigue load with a sinusoidal waveform was applied while the loading frequency is 5 Hz and the load ratio R ($R = P_{min}/P_{max}$, where P_{max} and P_{min} are the maximum and minimum loads in each fatigue cycle) is 0.1. The P_{max} was chosen to be 320 N herein, which is approximate 60% of the average fracture load obtained from static tests. An extensometer was used to monitor the crack opening displacement, again. The load and the crack opening displacement were continuously recorded with the same computer data-acquisition system as that for static fracture tests.

2.3. Microscopic observation of fracture surface

To investigate the mechanism of the fatigue crack propagation of the aluminum alloy foam, the fatigue fracture surfaces of CT specimens were observed using optical imaging. A comparison was conducted between the fracture surfaces of the aluminum alloy foam and those of traditional metal materials. Furthermore, the fractured specimens were examined using the FEI Quanta 400 scanning electron microscope (SEM) and the microscopic observation was conducted on the fracture surfaces. The fatigue fracture morphology was characterized and the fatigue crack propagation mechanism was summarized for the aluminum alloy foam.

3. Experimental results and statistical analysis

Based on the measured crack opening displacement, fatigue crack length is calculated by using the flexibility method. Then, we can obtain the relation between fatigue crack length a and load cycle number N of the aluminum alloy foam, namely the a–N curves, as shown in Fig. 2. It is seen that, the minimum value of the fatigue life of the CT specimens is only 4.2×10^4. In contrast, the maximum cycle value is 2.5×10^6, which is about 60 times larger than the minimum one. The large scatter in the fatigue life requires statistical models to analyze the fatigue crack propagation in the aluminum alloy foam.

Based on the a–N curves shown in Fig. 2, the fatigue crack propagation rates da/dN can be calculated for a given fatigue crack length a. At the same time, the stress intensity range ΔK can be calculated based on the crack length, the applied load and the dimensions of the CT specimen in accordance to the ASTM E647-11 standard. Then, the relationship between fatigue crack propagation rate da/dN and stress intensity range ΔK can be obtained, as plotted on a log-log graph shown in Fig. 3. It is evident that the fatigue crack propagation of the aluminum alloy foam has significant scatter and stochastic characteristics.

The da/dN-ΔK relationship is usually used to predict the residual