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Crack growth behavior under biaxial fatigue with phase difference ☆

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ABSTRACT

Crack growth behavior of aluminum alloy 7075-T6 was characterized under in-plane biaxial tension–tension fatigue with phase differences of 90° or 180° between the two applied orthogonal cyclic loads. The initial single crack, created under the biaxial fatigue without any phase difference, splits into two symmetric cracks under the biaxial fatigue with the phase difference. The split cracks grow without any further branching. Directions of split cracks deviate sharply from the direction of the initial single crack. Under both phase differences of 90° and 180°, lengths of both split cracks are almost the same at a certain number of cycle. Strain energy release rate versus crack growth rate relationships of the split cracks are almost equal to each other. Further, sum of strain energy release rates at a given crack growth rate of both split cracks is equal to that of a single crack under the biaxial fatigue without phase difference. Analytical and finite element analyses are presented to explain the splitting of a crack due to the phase difference between the applied biaxial cyclic loads.

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1. Introduction

It has been a common practice to characterize the fatigue crack growth in metals under the uniaxial loading condition. But the majority of aerospace structural components experience a combination of axial, bending, in-plane shear and torsional stresses, resulting in a complex stress state. It is thus appropriate to extend the fatigue crack growth studies to the non-uniaxial loading condition. One of many possible scenarios of the non-uniaxial loading conditions is the in-plane biaxial tension–tension fatigue with a phase difference between the applied loads, which is the focus of the present study. Cruciform-type specimens are generally used with a biaxial fatigue test machine to characterize the crack growth behavior under the in-plane biaxial loading condition. This arrangement provides a means to apply different types of loads in two perpendicular directions, e.g. different biaxiality stress ratios, loads with any phase difference, with same or different frequencies, etc.

Liu and Dittmer [1] investigated the fatigue crack growth behavior under different biaxial loading conditions in aluminum alloys. Their results showed that the direction of crack growth and crack growth rate are controlled by the larger biaxial stress component, and the stress parallel to the crack had small or negligible effect on the crack growth rate. Yuuki et al. observed that the biaxiality had negligible effect on crack growth rates at low stress levels, but noticeable effect at high stress levels [2]. Hopper and Miller found that stress parallel to crack causes decrease in crack growth rate [3]. Anderson and Garrett observed that the biaxial stress field causes an instantaneous or a gradual change in the crack growth rate [4]. Shanyavskiy's investigation showed that crack growth rate increases with the larger biaxiality stress ratio [5]. Sunder and Ilchenko [6] concluded that the fatigue crack growth rates are sensitive to the load biaxiality [6]. Lee and Taylor [7] reported that fatigue life is shortened with increase of the biaxiality stress ratio, but the crack growth rate versus crack driving force data was not characterized [7]. Joshi and Shewchuk [8] investigated the fatigue crack propagation in biaxial stress field using plates with cracks in bending mode, and their investigation also showed that the crack growth rates are affected by the stress parallel to the crack [8]. The authors and their colleagues have also investigated the biaxial fatigue crack growth behavior under ambient laboratory and saltwater environments for aluminum alloys, and these studies showed that crack growth rates and damage mechanisms vary with biaxial loads ratio and also they differ from their counterparts under the uniaxial fatigue [9–11].

Overall, fatigue crack growth studies under the in-plane biaxial loading conditions are limited unlike the uniaxial loading case. Further, there is still a need for the investigation of crack growth behavior under the cyclic biaxial loading condition with phase differences between applied loads, which leads to time-dependence

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of the biaxiality stress ratio during a fatigue cycle, to the presence of a sliding mode of surface displacement between crack surfaces (mode II), a curved crack path and formation of two fatigue cracks, as elaborated in this paper. These phenomena need investigation, which is the focus of the present study. This situation is similar to fatigue crack propagation in composite materials subjected to uniaxial fatigue, in which case it is a common practice to relate the crack growth rate with the strain energy release rate, G instead of the stress intensity factor, K [12]. So, a G-approach may be more appropriate to characterize the crack growth behavior under the biaxial fatigue, where the mode II crack surface displacement occurs as it does in this study. This is also important because of local anisotropy of cold-rolled metals including the aluminum alloy 7075-T6, which is the test material of this study. The direction and rate of the crack growth can be affected by the local anisotropy of properties that can create unique damage mechanisms [9–11]. Therefore, crack growth rate versus strain energy release rate approach was used in the present study to characterize the fatigue crack growth under the cyclic biaxial loading with phase differences between two orthogonal loads. This paper presents the details and results of these investigations. Finally, as far the authors are aware, there is no study available where phase difference is considered in the biaxial fatigue.

2. Material and methods

The test material of this study was 3.18 mm thick sheet of aluminum alloy 7075-T6, which is widely used as a structural material in the military and civilian aircrafts. In this study, tests were performed for investigating crack propagation behavior under cyclic biaxial sinusoidal loading with phase differences of 90° and 180° between two orthogonal fatigue loads, and comparison was made with the uniaxial fatigue and biaxial fatigue without any phase difference (i.e. in-phase). In this paper, the externally applied force per unit area in the horizontal direction is denoted as σ_x, and in the vertical direction as σ_y (Fig. 1). The biaxiality ratio is defined as the ratio of the horizontal force to the vertical force,

$$\lambda \equiv \frac{\sigma_x}{\sigma_y} \tag{1}$$

Cruciform specimens were machined from these sheets (Fig. 1). The length and width of each arm of the specimen was 120 mm and 45 mm, respectively, and a radius of curvature at the junction of arms was 45 mm. First, a hole of 6 mm diameter was drilled at the center of the specimen, and then a notch of 1 mm length and 0.25 mm width, at 45° to horizontal and vertical arms, was machined by electro-discharge method. After that, a precrack of 1 mm length, originating from the machined notch, was prepared

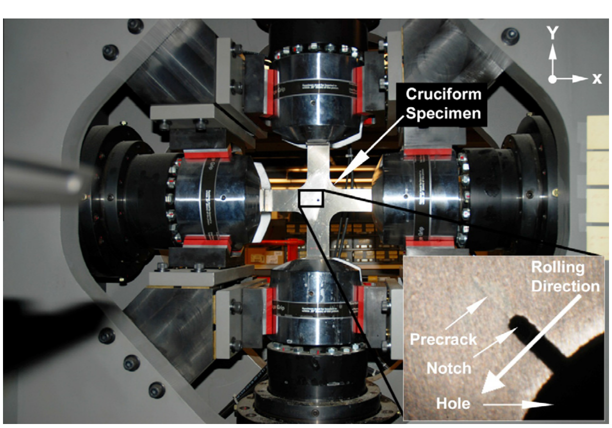

Fig. 1. Biaxial fatigue test setup with cruciform specimen.

by applying biaxial cyclic loads with biaxiality ratio $\lambda \equiv \frac{\sigma_x}{\sigma_y} = 1$ and without phase difference between the loads. The applied maximum and minimum loads during the precracking were the same as during the actual test. This resulted in a precrack that was colinear to the notch, as shown in the insert of Fig. 1. In a previous study [9], uniaxial fatigue crack growth tests have been conducted with the use of a precrack originating from the central circular hole. But the precrack was perpendicular to the applied load in the uniaxial fatigue tests. All cruciform and uniaxial specimens, in this and previous study, were machined in such a way that the notch and precrack were perpendicular to the rolling direction (Fig. 1) from the same batch material. A uniaxial test will be referred to as a test with $\lambda \equiv \frac{\sigma_x}{\sigma_y} = 0$.

A commercially available planar biaxial test system was used (Fig. 1). It consisted of two pairs of servo-hydraulic actuators and two-pairs of load cells with hydraulic grips in a rigid frame. This test machine was capable of applying the cyclic biaxial loads in vertical and horizontal directions independently, allowing to create the phase differences between the two applied cyclic loads. The stress ratio for the horizontal load was

$$R_x \equiv \frac{(\sigma_x)_{\min}}{(\sigma_x)_{\max}} = 0.5 \tag{2}$$

and the stress ratio for the vertical loading was the same

$$R_y \equiv \frac{(\sigma_y)_{\min}}{(\sigma_y)_{\max}} = 0.5 \tag{3}$$

This stress ratio was selected to minimize the effects of crack closure. A frequency of the both applied loads was 10 Hz.

During the tests, the crack growth was measured with the use of an optical microscope system, which consisted of a PixeLINK camera (resolution 3 mega-pixel) with an AF Micro Nikkor 200 mm lens. Optical images of the crack were recorded after certain numbers of cycles. These images were imported into the "uSCOPE" software, which was used for measuring the length of the cracks with a resolution of 0.01 mm. Further details are provided in [9].

Stress intensity factors and strain energy release rate were computed using a commercially available general-purpose finite element program, Abaqus [13]. To take into account the phase differences between the applied loads, the finite element analysis was performed in a dynamic mode, where the cyclic biaxial loads were applied with the phase difference of either 90° or 180°. The mesh details are shown in Fig. 2a and b. The strain energy release rate G, the mode I stress intensity factor K_I and the mode II stress intensity factor K_{II} are related as:

$$G = \frac{K_I^2}{E} + \frac{K_{II}^2}{E} \tag{4}$$

where E is the Young's modulus.

The maximum and minimum external forces per unit area, applied to the both arms of specimen, were equal

$$(\sigma_x)_{\max} = (\sigma_y)_{\max} \tag{5}$$

$$(\sigma_x)_{\min} = (\sigma_y)_{\min} \tag{6}$$

and the frequency of the applied forces was $\nu = 10$ Hz. The time variation of the applied remote stresses was

$$\sigma_x(t) = \frac{(\sigma_x)_{\max} + (\sigma_x)_{\min}}{2} + \frac{(\sigma_x)_{\max} - (\sigma_x)_{\min}}{2}\cos(2\pi\nu t) = \frac{(\sigma_x)_{\max}}{2}[1 + R_x + (1 - R_x)\cos(2\pi\nu t)] \tag{7}$$

$$\sigma_y(t) = \frac{(\sigma_y)_{\max} + (\sigma_y)_{\min}}{2} + \frac{(\sigma_y)_{\max} - (\sigma_y)_{\min}}{2}\cos(2\pi\nu t + \gamma) = \frac{(\sigma_y)_{\max}}{2}[1 + R_y + (1 - R_y)\cos(2\pi\nu t + \gamma)] \tag{8}$$