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Fatigue life prediction of aviation aluminium alloy based on quantitative pre-corrosion damage analysis

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Abstract: A new method of quantitative pre-corrosion damage of aviation aluminium (Al−Cu−Mg) alloy was proposed, which regarded corrosion pits as equivalent semi-elliptical surface cracks. An analytical model was formulated to describe the entire region of fatigue crack propagation (FCP). The relationship between the model parameters and the fatigue testing data obtained in the pre-corroded experiments, crack propagation experiments and *S*−*N* fatigue experiments was discussed. The equivalent crack sizes and the FCP equation were used to calculate the fatigue life through numerical integration based on MATLAB/GUI. The results confirm that the sigmoidal curve fitted by the FCP model expresses the whole change from Region I to Region III. In addition, the predicted curves indicate the actual trend of fatigue life and the conservative result of fatigue limit. Thus, the new analytical method can estimate the residual life of pre-corroded Al−Cu−Mg alloy, especially smooth specimens.

Key words: pre-corroded aluminium alloy; corrosion pit; crack propagation; life prediction; fatigue limit

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1 Introduction

Aluminium alloys are widely used in military and aerospace industries owing to their low density, high strength and favourable mechanical properties [1−3]. However, the material is not only subjected to fatigue loading but also affected by corrosive environment, such as salt water and/or salt fog [4−8]. The longer the service time of the structure of aircrafts has, the more serious the corrosion damage becomes. The corroded surface can easily produce corrosion pits and then lead to significant reduction of fatigue life [9,10]. Hence, corrosion is recognized as a primary aging mechanism that affects the long-term reliability, durability and integrity of aircrafts.

The corrosion damage is the critical problem to reduce original material properties and make accurate prediction of fatigue life extremely difficult. Various researchers have studied this problem from the following aspects. According to the morphology features of corrosion pits observed by SEM, their geometrical shape was reduced to an initial semi-circular or semi-elliptical surface crack [11−15]. Afterwards, using probabilistic methods, numerical techniques, FEM, etc. [10,16−18], its characteristic parameters were also identified to be the key factor determining pre-corroded damage degree, residual fatigue strength and crack propagation rate. On the other hand, new methods were proposed based on fractal dimension [19] or fracture mechanics [20−22]. Relevant analytical softwares, such as NASGRO and FLAGRO [23−27], were applied to calculating the life of specimens and structures. Nevertheless, the research of pitting corrosion [28] demonstrated that the cross-sectional shape of corrosion pits slowly changed from approximate semi-circle to elongated semi-ellipse with the increase of corrosion time. As a result, the accuracy and precision of life prediction are limited by the fixed sizes of equivalent cracks assumed in the above methods. Hence, the relationship between the quantitative technique of pre-corrosion damage and the prediction method of fatigue life has great significance in aircraft structure design and engine life assessment.

Fatigue life is generally expressed as the sum of two segments: the life of fatigue crack initiation and propagation [29−31]. Because the life of pre-corroded aluminium alloy decreases sharply under the effect of

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pre-corrosion damage, it is well recognized by now [15,32−34] that the crack initiation life only accounts for less than 20% of the total life. In the life predication, therefore, it is convenient to ignore this part and directly compute the crack propagation life. Based on this hypothesis, the primary innovative point is to quantify the corrosion pit as a semi-elliptical surface crack, which changes with the pre-corrosion time. In this work, the sizes of equivalent cracks were controlled by the data of short crack propagation experiment. Moreover, an entire region FCP model based on fracture mechanics was formulated to predict the fatigue life of pre-corroded aluminium alloy. The predicted results were eventually verified by comparing with the experimental data of *S*−*N* fatigue curves.

2 Experimental

2.1 Material and specimen preparation

Experimental specimens were cut out of the Al−Cu−Mg alloy. They were supplied in the form of flat bare sheets with a thickness of 2 mm. The sizes of smooth specimens, M(T) specimens and SENT specimens are provided in Fig. 1, respectively. The surface of each specimen was polished with the 600 grit sandpaper to eliminate burrs and then scrubbed by cotton ball dipped in acetone solution.

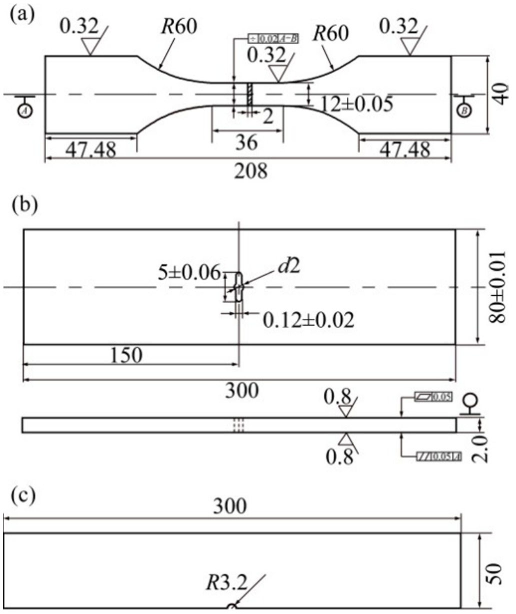

Fig. 1 Schematic diagrams of specimen sizes: (a) Smooth specimen; (b) M(T) specimen; (c) SENT specimen (unit: mm)

2.2 Pre-corrosion experiments

According to the ASTM standard [35] and the environmental characteristics of aircraft service, the numbered specimens were alternately corroded in 3.5% NaCl solution at test temperature of (25±5) °C for 2, 24, 72, 120, 240 and 480 h, respectively. The solution was continuously cycled by a small water pump to maintain the constant concentration. The ratio of solution volume to specimen surface area was 10−30 mL/cm^2. After corrosion, all surfaces of the specimens were scoured with flowing water in more than 15 min, before being wiped, blown dry by a hair-dryer, and reserved in the drying cabinet.

After corrosion for a period of time, the specimen surface becomes rough with the obvious change of its colour from light grey to dark green, as shown in Fig. 2. The depths of corrosion pits after corrosion for 2, 24, 72, 120, 240 and 480 h were measured by a 3D stereo microscope, and experimental data points and a fitted exponential curve are shown in Fig. 3. It had been shown in previous study [34] that the corrosion rate of alloys changed steadily with the increase of corrosion time, so an exponential function was proposed to express the non-linear relationship between the pre-corrosion time and the depth of corrosion pits. Its coefficients were determined by fitting the measured data based on the least square method. This equation expression is described as

$$a_0=1.235t^{0.775} \tag{1}$$

where a_0 is the depth of corrosion pits and t is the pre-corrosion time.

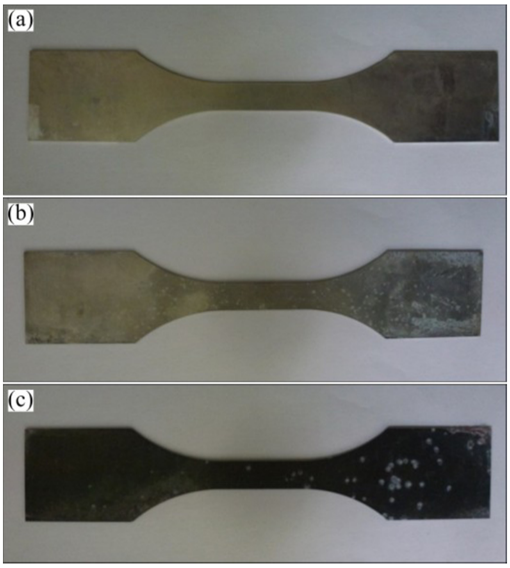

Fig. 2 Pre-corroded specimens after corrosion for 24 h (a), 240 h (b) and 480 h (c)

2.3 Long and short crack propagation experiments

In the laboratory environment, M(T) specimens and SENT specimens were used in the experiments of long and short crack propagation, respectively. After being pre-corroded for 24 h and 240 h, they were tested on a 100 kN servo-hydraulic fatigue machine with digital closed loop control in PC (MTS 810). The stress

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