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Effect of alternate corrosion factors on multiaxial low-cycle fatigue life of 2024-T4 aluminum alloy

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A B S T R A C T

Due to the seawater splash, rain water scouring and prolonged exposure, the aircrafts serviced in sea-coast or marine environment always suffered liquid corrosion effects under certain temperature. 2024-T4 aluminum alloy had been widely used in aircrafts fuselage. During service, the actual process was close to the alternate mode of "Ground Corrosion + Air Fatigue", in which alternate corrosion factors had greatly effects on multiaxial fatigue life of 2024-T4 aluminum alloy. For the purpose of evaluating the influence of alternate corrosion time, corrosion temperature, corrosion solution flow rate and pH value on the fatigue performance, a multi-parameter regulated liquid corrosion device was designed. Multiaxial fatigue tests were performed under constant amplitude sinusoidal wave loading with constant tension-torsion ratio $\sqrt{3}$ in air. The fracture was observed by scanning electron microscope. The results indicated a reduction tendency of multiaxial fatigue life with the increase of alternate corrosion time, corrosion temperature and corrosion solution flow rate as well as the decrease of pH value. The influence order of relevant factors was: alternate corrosion time > corrosion temperature > corrosion solution flow rate > solution pH value. The effects of alternate time and temperature immersed in solution on corrosion resistance of 2024-T4 aluminum alloy are investigated by potentiodynamic polarization experiments and electrochemical impedance spectroscopy (EIS) tests. The observed mechanical behavior and associated phenomena were directly linked to microstructure characteristics such as corrosion pits and micro-cracks. The cyclic hardening appeared in both axial and tangential direction at the beginning stage. With the consideration of corrosion effect on the fatigue property, the equivalent corrosion life was proposed to characterize the influence of corrosion and to predict the alternate corrosion - fatigue life. Fine results were obtained with all data in 2× scatter band.

1. Introduction

2024-T4 aluminum alloy is extensively applied considering its properties of high strength ratio, low density and brilliant heat performance [1–3]. A large number of 2024-T4 aluminum alloy components in aerospace vehicles are usually subjected to multiaxial load. Even if some components are in the case of uniaxial loading, they are also subjected to the local multiaxial load for the increase of structure complexity and integrity. Therefore, the theory of the uniaxial fatigue is not enough to explain the fatigue phenomenon comprehensively. Recently, Yu et al. [4] studied the crack growth of 7075-T651 aluminum alloy under mixed mode of proportional and non-proportional loads. The results indicated that for the most non-proportional load conditions, the crack path direction couldn't be predicted with the traditional maximum tangential stress criterion. Szusta et al. [5] concentrated on the experimental studies of low-cycle multiaxial fatigue performance of 2024-T3 aluminum alloy at elevated temperature. Tomczyk et al. [6] pointed out that both temperature and pre-deformation had influences on cyclic properties of 2024 aluminum alloy. In fact, the preliminary strain greatly affects the fatigue life of the mechanical joints used in frame and shells manufacture of the aircraft fuselage and wings [7,8].

During the service of the aircraft, corrosion and fatigue are important failure modes which often limit the overall service life. The effect of corrosion on materials' fatigue properties attracted the researchers' attention. Many researchers had reported that environmental factors enhance the development of corrosion, making the corrosion - fatigue interaction acutely pertinent to the structural integrity of airframes based in sea-coast or marine

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environments [9–15]. Li et al. [16] examined the initiation and early expansion of micro-cracks at corrosion pits with the Scanning Electron Microscope (SEM). The results showed a number of crack origins around the pits and the early expansion of fatigue crack was K_I/K_{II} mixed mode. Menan and Hénaff [17] carried out corrosion fatigue tests on 2024 aluminum alloy in different corrosion environments. It was demonstrated that fatigue and corrosion had a synergistic effect on crack growth. The methods and related factors were discussed to calculate fatigue crack growth [18–21]. Huang et al. [22] conducted pre-corrosion fatigue tests on 7075-T6 aluminum alloy and analyzed correlated coefficients for corrosion cracks and cracks according to Pearson method. Equivalent crack size model was developed for both single crack and multi-crack initiations with different stress levels. Ishihara et al. [23] proposed a pit depth function of both stress and corrosion time. It was demonstrated that a threshold stress could divide the specimen life into crack initiation and crack propagation, and pit growth rule could help to predict the fatigue life. Huang et al. [24] performed corrosion fatigue experiment to study the pitting behaviors under both proportional and non-proportional loadings. The results showed that for the proportion case, the pitting condition was more serious.

The damage state of the aircraft in-service environment is simulated by the alternate corrosion-fatigue test mode, that is, the alternate process of corrosion on ground and fatigue in air. During high-altitude flights, the damage caused by fatigue loading is predominant, and the effect of corrosion damage in high-altitude environment is negligible for the thin air and low temperature. While when the aircraft parks in the airport, there is no fatigue loading, and the structure damage caused by corrosion is pronounced. Menan et al. [25] discussed the influence of loading frequency and alternate mode on the corrosion fatigue crack growth. Li et al. [26] used 7B04 aluminum alloy to carry out alternate test of corrosion and fatigue with the purpose of investigating the reliability life. Vucko et al. [27] evaluated fatigue performance of joined assemblies in corrosion environment with alternate corrosion fatigue mode. A research on the multiaxial fatigue behavior of 2024-T4 aluminum alloy with different pre-corrosion time and alternate corrosion modes was conducted in the authors' research lab, which has been reported in Ref. [28]. But at present, few references have been found in the literature reporting about alternate corrosion-multiaxial fatigue associated with certain temperature corrosion solution.

Aiming at simulating of “Ground Corrosion + Air Fatigue” state for in-service aircraft and studying the effect of corrosion environmental factors on multiaxial fatigue properties, accelerated alternate corrosion multiaxial fatigue tests were done in this paper. Four parameters which might affect the alternate corrosion-multiaxial fatigue life were discussed by orthogonal experiments. Cyclic loading curves and fracture morphology were analyzed to point out the mechanism of the fracture in different corrosion conditions. Potentiodynamic polarization experiments and electrochemical impedance spectroscopy (EIS) tests were carried out to investigate the effects of alternate corrosion time and temperature. The equivalent corrosion life was newly proposed to predict the alternate corrosion multiaxial fatigue life.

2. Experimental procedures

2.1. Material and specimens

For this research, 2024-T4 aluminum alloy was selected to be the test material with the normal chemical composition of 0.1% Cr, 3.8%–4.9% Cu, 0.5% Fe, 1.2%–1.8% Mg, 0.3%–0.9% Mn, 0.5% Si, 0.15% Ti, 0.25% Zn (mass fraction) and balance is Al. The material had a tensile yield stress of 373.7 MPa, a tensile ultimate stress of 526.8 MPa and an elastic modulus of 72 GPa. The specimen for multiaxial fatigue test is in form of tapered round bar with a maximum diameter of 24 mm and a minimum diameter of 12 mm. Its specific dimension is indicated in Fig. 1.

2.2. Experimental methods

For accelerated alternate corrosion multiaxial fatigue tests, specimens were firstly corroded for a certain unit corrosion time (in hours), then were subjected to unit multiaxial fatigue loading which equaled to 6000 cycles. The model of “corrosion + fatigue” is a basic alternate test unit. Alternate tests were conducted as test unit until specimens came into fracture. For each condition, 5 specimens were tested to obtain the distribution of fatigue life.

2.2.1. Multi-parameter regulable liquid corrosion device

A specific device was designed as shown in Fig. 2 to conduct the corrosion test. It contains the constant pH supply module (CPSM), flow rate regulator module (FRRM), constant temperature reaction module (CTRM) and corrosion solution back-flow module (CSBM). The CPSM is composed of (1) beaker, (2) water bath, (3) pH probe, (4) pH adjustment device, (5) supply pump of pH regulating solution and (6) cylinder of pH regulating solution. The FRRM is a (7) pump whose flow rate is adjustable. A (8) self-made corrosion box acts as the CTRM. The CSBM works through a (9) return pipe. It is a liquid corrosion device with the function of controllable temperature (20 °C-80 °C), controllable pH value (0-14) and adjustable flow rate. The flowing liquid corrosion experiments are all conducted with it.

2.2.2. Alternate corrosion test

After ultrasonically cleaned by acetone and alcohol respectively, specimens were corroded under different corrosion environment factors with the corrosion device mentioned above. The corrosion solution used in this paper was 20% EXCO (an immersion test in accordance with ASTM G34 [29]). The factors included alternate corrosion time (4 h, 6 h and 8 h), corrosion temperature (35 °C, 55 °C and 75 °C), pH value (1.5, 4 and 7) and flow rate (25 ml/min, 35 ml/min and 45 ml/min) of the corrosion solution.

Firstly, the orthogonal experiment including four factors with three levels was applied to analyze the influence degree of factors on the fatigue life. Secondly, in order to further judge the possible effect of different factor levels, experiments under the condition of single–factor test were conducted: (1) alternate corrosion time and corrosion temperature were variables at pH1.5 and flow rate of 25 ml/min. Alternate corrosion time were 4, 6 and 8 h, respectively. Corrosion temperature were 25, 35, 55 and 75 °C, respectively. (2) pH value and flow rate of the corrosion solution were variables with

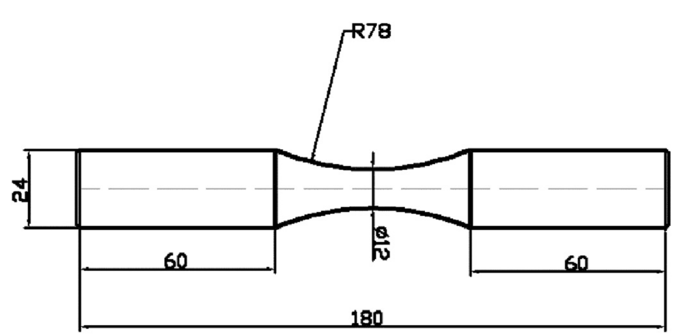

Fig. 1. Fatigue specimen dimension (Unit: mm).