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Influence of microstructure on fatigue crack propagation behaviors of an aluminum alloy: Role of sheet thickness

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ABSTRACT

Fatigue crack propagation behaviors of Al-Cu-Mg alloy sheets with the thickness of 30 mm and 55 mm were investigated by means of optical microscope, scanning electron microscope, transmission electron microscope and electron back scatter diffraction (EBSD) analysis technique. The results show that, the crack propagation rate of 30 mm sheet appears more sensitive to the variation of stress intensity factor dispersion at the crack tip in the stable crack propagation stage, and the crack propagation rate is slower. The precipitation strengthening phase, coarse particles, grain boundaries, sub structure, grain micro orientation and other microstructure have a very significant influence on fatigue crack propagation behaviors. The precipitation strengthening phase, grain boundaries and sub structure have a positive significance to delay the fatigue crack propagation rate. The coarse particles will locally accelerate the fatigue crack propagation and grain micro orientation affects the path selection of fatigue crack propagation in grains and grain boundaries.

1. Introduction

The studied aluminum alloy (Al-Cu-Mg) is a typical 2124 aluminum alloy, a new type of high strength aluminum alloy developed on the basis of 2024 aluminum alloy by reducing the content of iron, silicon and other impurities, and normally it is usually used in T351 and T851 state [1,2]. As a representative of 2000 system aluminum alloy, the alloy was firstly applied on the Boeing 777 aircraft, and later was applied on the A380 passenger plane, belonging to a new generation of aerospace structural materials and considered to be the most ideal aircraft skin material currently [3–5].

There have been research reports about Al-Cu-Mg alloy, especially the research work on the heat treatment technologies, microstructure and fatigue performance of alloy under different conditions was progressing smoothly [6–10]. Bray et al. [11] studied and found that the aging time with the minimum value of crack propagation rate of 2024 aluminum alloy relative to the stage of the precipitation phase transited from the GPB (Grain Boundary Precipitated) zone to the S phase after aging treatment at different time. By means of X ray diffraction and electron backscatter diffraction, Ludwing et al. [12] found that, when the crack propagated to the boundaries, the crack would continue to propagate when a certain angle appeared between the crack orientation and the slip surface of adjacent grains, and the propagation would be hindered if a torsion appeared between the crack orientation and the slip surface of adjacent grains by studying the effects of grain boundaries and grain orientation on short crack propagation in alloy. Lingigkeit et al. [13] found that, with the increase of grain size,

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the crack propagation rate decreased, but there was no significant relative relationship between the crack propagation rate and grain size in the corrosion environment. Haigen Jian et al. [14]established the fatigue crack propagation-torsional model through the crystallographic analysis of the fatigue crack propagation behaviors of B93 aluminum alloy. At present, the influences of grains, grain boundaries, sub structure, precipitation phase, micro orientation and other microstructure on fatigue performance and fatigue crack propagation behaviors have become a hot spot of fatigue failure analysis of aluminum alloy [15–17]. However, based on the microstructure, the investigation about the influences of sheet thickness on fatigue crack propagation rate, especially the influences of thickness size on crack propagation behaviors have been seldom reported.

The fatigue crack propagation rates of 30 mm and 55 mm sheets were analyzed contrastively in this paper. The relationship between the microstructure and fatigue crack propagation behaviors of Al-Cu-Mg alloy sheets was investigated according to the perspective of precipitation strengthening phase, coarse particles, grain boundaries, sub structure, grain micro orientation and other microstructure, so as to explore the effect mechanism of microstructure on the fatigue life of aluminum alloy (Al-Cu-Mg). Which will have an important reference value and research significance for delaying the fatigue crack propagation rate, improving the prediction accuracy of fatigue life and determining the critical thickness of sheets in actual service.

2. Experimental material and methods

The aluminum alloy (Al-Cu-Mg) sheets with the length of 40 mm, width of 1000 mm were employed as the test material. After sawing and milling, hot rolling and obtaining two kinds of sheets with the thickness of 30 mm and 55 mm, respectively. Then solid solution (470 °C, 60 min)-pre stretch (2%)-artificial aging (115 °C, 8 h + 165 °C, 16 h) treatments were carried out to obtain the final test material of T851state. The specific chemical composition is shown in Table 1.

The compact tension specimen (CT specimen) was selected to carry on the fatigue crack propagation rate test according to the GB/T 6398-2000 national standard [18], and the specimen size was shown in Fig. 1. Three specimens were machined at each thick sheet. Fatigue crack propagation rate test was conducted on the MTS810-50KN type fatigue test machine and the maximum load was 10kN with sine-wave loading way of 10 Hz and a stress ratio of R = 0.1 at room temperature and atmospheric environment. A series of testing ΔK and the corresponding (da/dN) data was obtained.

The difference of sheets thickness was caused by the reduction in thickness in the process of hot rolling and the influence on the microstructure of alloy sheets was mainly embodied in the grain size, grain boundaries number and sub structure. In order to observe the effects of grain size, grain boundaries and sub structure on the fatigue crack propagation, fracture morphology analysis, optical microscope and TEM (Transmission Electron Microscope) microstructure observation of sheet specimens with the thickness of 30 mm and 55 mm were carried out, respectively. Metallographic experiment was carried out on the ROLYVER-MET metallographic microscope, corroded by the Keller reagent with the ratio of $2.5mlHNO_3 + 1.5mlHCl + 1mlHF + 95mlH_2O$; Sirion field emission scanning electron microscopy with energy spectrum was used to observe the scanning morphology; TEM observation was carried out on the Tecnai G 2005 electron microscope. At the same time, in order to explore the influence of micro orientation on fatigue crack propagation, 30 mm sheet was chosen to carry on the fatigue crack propagation morphology observation and EBSD orientation analysis, the termination condition of crack propagation test is $\Delta K = 15\ MPa\cdot m^{1/2}$.

3. Experimental results and analysis

3.1. Fatigue crack propagation rate

The relationship curves of fatigue crack propagation rate da/dN and the stress intensity factor dispersion ΔK at the crack tip of two different thick sheets are shown in Fig. 2. Under the same experimental condition, three curves at each thickness are obtained, which exhibit a good coincidence. As can be seen from Fig. 2, curves of fatigue crack propagation rate exhibit the characteristics of three distinct period, which are correspond to the three stage of fatigue fracture (crack initiation, stable crack propagation and crack instability). Extending the curve and intersecting with the abscissa in the stage I, the threshold value ΔK_{th} is gotten. Comparing Fig. 2a and b, the threshold values of fatigue crack propagation of two kinds of thick sheets are close to that of 7 $MPa\cdot m^{1/2}$, which reveals that the thickness of Al-Cu-Mg alloy sheet has no significant effect on the fatigue crack initiation. Two kinds of sheets are in the stable crack propagation stage (stage II) when the ΔK is about 10–11 $MPa\cdot m^{1/2}$, obviously, the thicker the sheet, the faster the crack propagation speed in this stage. For example, when $\Delta K = 16\ MPa\cdot m^{1/2}$, the da/dN of 30 mm sheet is about $4.29\cdot 10^{-4}$mm/cycle, while the da/dN of 55 mm sheet is about $4.81\cdot 10^{-4}$mm/ cycle. In addition, the thicker the sheet, the earlier the crack propagation into stage III, namely, the crack

Table 1
The chemical composition of Al-Cu-Mg alloy (mass fraction, %).

Cu	Mg	Mn	Fe	Si	Cr	Ti	Zn	Al
4.22	1.40	0.56	0.20	0.12	<0.05	<0.12	<0.25	Bal.