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Effect of creep aging forming on the fatigue crack growth of an AA2524 alloy

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ABSTRACT

Effects of creep aging forming on the microstructural evolution, conventional mechanical properties and fatigue crack propagation (FCP) behavior for 2524 aluminum alloy were studied by tensile and hardness testing, the FCP behavior testing and transmission electron microscopy (TEM) observation. The results show that in the low stress intensity range, the characteristics of precipitates have a significant effect on fatigue performance of the creep-aged aluminum alloy, and the mainly precipitated S'' phases in the alloy creep-aged for 4 h is beneficial to the reversibility of coplanar slip and dislocation slip, and the alloy presents better FCP resistance and relatively lower FCP rate, while the FCP rate increases with increasing aging time. In the Paris regime, effects of microstructure on the FCP rate are no longer obvious, and the FCP rates are almost consistent. Meanwhile, the presence of creep stress significantly accelerates the aging precipitation process. In terms of yield strength $\sigma_{0.2}$, hardness and FCP resistance, the 9 h artificial aged alloy is analogous to the 4 h creep aged alloy. The peak strength of the alloy creep-aged for 24 h is the highest, but the fatigue crack growth resistance degraded obviously. It is not comprehensive to determine the optimal process of creep aging only in accordance with the peak strength.

1. Introduction

Creep aging forming (CAF) technology is a type of forming method synchronizing forming and aging treatment by utilizing the creep characteristics of metal, and the forming products boast such advantages as excellent structural integrity, high moulding precision and low residual stress [1]. This technology has been widely applied in the aerospace field, including the wing skin of the Airbus A380 [2], the wing panels of B-1B Bombers manufactured by Textron in the United States [3], and the integral panel of the International Space Station capsule [4]. Creep aging forming technology has extensive application values and prospects, as a research hotspot currently studied by scholars of various countries [5–8].

Pitcher et al. [7] analyzed the performance of AA2024, AA8090 and AA7449 after creep age forming, and discussed the feasibility of manufacturing aircraft skin and aircraft panels with CAF. Zhan et al. [9,10] studied the differences in the performance of AA2124 creep-aged and artificially aged at 185 °C. The study suggested that compared to the alloy under the conventional artificial aging treatment, the peak strength of the alloy after creep aging treatment greatly increased, but the plasticity decreased. At the same time, TEM observation showed that the presence of stress accelerated the dislocation propagation and promoted the precipitation of precipitates, and resulted in the uneven distribution of S' phases. The effect of microstructure on the hardening and creep behavior of AA7075 was studied by Arabi [11]. The results indicated that the number of precipitates decreased with increasing forming time and temperature but the space between precipitates increased, and the precipitation free zone (PFZ) was widened. Taking the Al-Li-S4 alloy as the research object, Wang et al. [12] studied the effect of pre-deformation on the creep behavior. The research held that prestress could accelerate the steady creep rate and improve the total creep strain, but the creep strain of the alloy after pre-deformation treatment is less than that of the alloy without pre-deformation treatment. The pre-deformation can promote the precipitation of T_1 and θ phases, while reduce the precipitation of δ phases.

AA2524-T3 is considered to be the best aluminum alloy of aircraft skin currently with excellent performance, and widely applied in the aviation field [13,14]. Yin et al. [15] and Shou [16] researched the effects of different grain sizes on the FCP rate of AA2524. Yin argued that the grain refinement resulted in a decrease in the fatigue resistance

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of the alloy, and Shou suggested that the crack growth rate was the lowest with the grain size in the range of 50–100 μm. However, the grain size of the alloy during the creep process did not change significantly, and the influence of different aging conditions did not be considered in their research. Bray et al. [17] studied the effect of different aging parameters on the FCP behavior of the 2000-series aluminum alloys. The study suggested that environmental fatigue crack growth rate decreases at initial artificial aging, and then increases with increasing aging time, and overaging does not improve cracking resistance. But the effect of stress on artificial aging was not taken into consideration in the study.

At present, the researches on creep aging forming technology mainly focus on the creep behavior and mechanical properties of materials under different process parameters, and usually take the peak strength as the basis for determining the optimal creep aging process [9,18]. In fact, among all the aircraft parts,fatigue failure is most likely to occur in the aircraft skin and wings, due to such factors as frequent take-off, landing, gusts, etc. [19]. For aerospace parts, the FCP resistance is one performance indicator of vital importance. Different microstructural characteristics of the alloy affect the fatigue performance at each different stage [20,21]. Currently, there are few studies on the effect of creep aging process parameters on the microstructure and fatigue crack growth rate of aluminum alloys. In this paper, 2524 aluminum alloy as a typical Al-Cu-Mg alloy was used to study the effect of creep aging process on microstructure and the FCP behavior.

2. Material and experiments

The high-strength 2524-T3 aluminum alloy used for this work was provided by China Southwest Aluminum Group. The as-received condition was solution heat treated, stretched, and naturally aged. The chemical composition of AA2524-T3 is shown in Table 1.

2.1. Creep aging forming experiment

Creep aging forming experiment was completed in the autoclave by vacuum loading. As its formation principle shown in Fig. 1, the specific experiment process was divided into 3 steps as follows:

Preparation (step 1): placing the aluminum alloy plate in the center of the mould (radius of curvature ρ = 1000 mm), then wrapping the mould and plate with ventilated felt and vacuum bag.

Loading and creep aging (step 2): vacuuming the bag, and the plate would be elastically deformed under even loading until it fully fits the mould surface.placing the deformed plate and mould together in the autoclave, and setting creep temperature, aging time, and the heating rate of 1.5 °C/min. At this stage, the plate underwent creep, stress relaxation, and the change of microstructure, leading to elastic deformation partially converted to permanent creep deformation.

Unloading (step 3): removing the load and temperature after creep aging. The desired shape was obtained after springback.

The experiment consisted of four groups, and case 1, 2 and 3 were creep-aged at the temperature of 180 °C with holding time of 4 h, 9 h, and 24 h respectively, the curvature radius of the mould ρ = 1000 mm, and the applied stress field of 0.1 MPa. Case 4 was artificial aged (AA) without stress. The specific setting parameters are shown in Table 2.

2.2. Conventional mechanical properties and FCP testing

Specimens for tensile testing, hardness testing, FCP testing and microstructural analysis were cut from the formed plate by wire-electrode cutting. Tensile properties testing was performed in accordance with ASTM-E8M [22], and conducted at room temperature on SUST-CMT5105 tensile machine with the strain rate of 2 mm/min. Hardness testing was conducted on HVS-1000Z micro-digital hardness tester with 3 kN load and 15 s holding time. Each sample was tested at 5 points and the average value was regarded as the hardness value.

Constant load amplitude fatigue tests were performed in accordance with ASTM-E647 [23]. The tests were conducted at room temperature on MTS-810 fatigue tester with stress ratio (R, $R = \sigma_{\min}/\sigma_{\max}$) of 0.5, loading frequency of 10 Hz and sine waveform loading. The specimens were of the compact tension geometry, as its dimensions shown in Fig. 2. The stress intensity factor range, ΔK, was calculated by following equation [23]:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}}\cdot\frac{(2+\alpha)}{(1-\alpha)^{3/2}}(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \tag{1}$$

where $\alpha = a/W$, a is the crack length measured by crack opening displacement (COD) gauge, W is the specimen width, ΔP is the load range, and B is the specimen thickness.

2.3. Microstructural observations

The transmission electron microscope (TEM) observations were performed on the Tecnai-G220 microscope operating at 200 kV. TEM test samples were thinned mechanically to 60–80 μm first, punched into disks with a diameter of 3 mm, and then thinned again with the Tenupol-5 electro-polished double spraying thinner machine in 30% HNO_3 and 70% CH_3OH mixed solution at − 30 °C to − 25 °C, using a voltage of 15 V.

3. Results and discussion

3.1. Effect of creep aging forming process on microstructure

Fig. 3 shows the microstructures of the grains (Fig. 3a) and grain boundaries (Fig. 3b) of AA2524-T3 as received. This naturally aged condition at room temperature did not promote the precipitation of precipitates effectively, so no strengthening phase occurred in grains but the accumulation of some solute atoms. There are mainly GP zones in grains [24]. Meanwhile, a number of short-rod-shaped secondary phases can be found in Fig. 3. These phases are T phases ($Al_{20}Cu_2Mn_3$) with medium submicron size, incompletely dissolved after solution treatment. These coarse T phases are not coherent with the matrix, and are likely to act as a source for crack nucleation. Some T phases occur at grain boundaries, but no precipitate neither. Besides, there is no obvious precipitation free zone (PFZ) near the grain boundaries.

Fig. 4 shows the microstructures of the grains and grain boundaries of case 1, case 2 and case 3, creep aged for 4 h, 9 h and 24 h respectively. After 4 h creep-aging (case 1), apart from T phases in the aluminum alloy matrix (Fig. 4b), some tiny transition phases, S'' phases, occurred in grains. But due to the short aging time, precipitates were relatively less with small size. At the same time, neither the presence of precipitates nor the formation of PFZ occurred near grain boundaries. The alloy then was at the underaged condition. When the creep aging time was extended to 9 h (case 2), a large number of needle-shaped S' phases (Fig. 4c) were precipitated in grains with the size of 80–125 nm. These precipitated phases are of smaller size and larger quantity, with greater pinning effect on dislocation. Precipitates and PFZ (Fig. 4d) with the size of about 66.7 nm can be observed at grain boundaries. The alloy then was at the peak aged condition. At the aging time of 24 h (case 3), a large number of coarse needle-shaped S phases (Fig. 4e) occurred in grains with the size of about 200 nm, and due to the long presence of stress, more vacancies moved to the center of dislocation loop (Fig. 4e). Because of the longer aging time, strengthening phases at

Table 1
Chemical composition of 2524 Al alloy (wt%).

Cu	Mg	Mn	Fe	Zn	Si	Ti	Cr	Al
4.26	1.36	0.57	0.03	0.024	0.089	0.01	0.002	Bal