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Effect of isothermal and non-isothermal aging on the low cycle fatigue behavior of an Al–Cu–Mg–Si forging alloy

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ABSTRACT

Low cycle fatigue (LCF) behavior of an Al–Cu–Mg–Si forging alloy was investigated at room temperature. Isothermal aging (T6) and non-isothermal aging (NIA) treatments were applied to produce different microstructures. Under the same strain amplitude, the LCF life of NIA specimen exceeded that of T6 specimen. Besides, NIA specimens exhibited cyclic stability behavior in contrast to cyclic hardening behavior of T6 specimens. The different LCF behaviors could be rationalized by different deformation mechanisms under cyclic straining. T6 specimens with non-shearable θ′-phases underwent Orowan bypassing mechanism leading to the cyclic hardening behavior. While NIA specimens with shearable and non-shearable θ′-phases suffered from both particle shearing and Orowan bypassing mechanisms resulting in the cyclic stability behavior. Non-shearable θ′-phases bypassed by dislocations introduced more stress concentration, while shearable θ′-phases cut through by dislocations caused less stress concentration. Therefore, fatigue life of NIA specimen is longer than that of T6 specimen.

1. Introduction

Al–Cu–Mg–Si forging alloys are important materials for making aircraft landing gear hubs because of their remarkable combination of high damage tolerance, high corrosion resistance and excellent workability [1–4]. As a load-bearing structural component, the aircraft landing gear hub is often subjected to constant and variable amplitude loading. Therefore, fatigue is an important issue that should be considered when designing such components. In general, stress imposed on rotating components decreases during cruise period and the components typically suffer from high cycle fatigue (HCF) [5]. However, the aircraft landing gear hub would undergo greater stress in the course of take-off and landing operations, thus low cycle fatigue (LCF) performance is considered for the fatigue design of Al–Cu–Mg–Si alloys applied in aircraft landing gear hubs.

As conventional aerospace aluminum alloys, Al–Cu–Mg–Si alloys are usually used as isothermal-aged T6 temper and exhibit high strength, which generally results in improved performance of the stress controlled HCF [6, 7]. However, these high strength conditions are subjected to poor ductility and exhibit a relatively reduced fatigue life in the strain controlled LCF regime [8]. Thus, a lot of researches have done to solve the issue of reduced LCF life by improving ductility without sacrificing strength of the materials. Refs. [9–13] have shown that thermo-mechanical treatment (TMT) can get excellent comprehensive material properties by introducing plastic deformation between solution and aging procedures. However, the TMT processing is more likely to be used in sheet materials rather than the large forging components. Fortunately, recent studies [14–16] have shown that a novel method of non-isothermal aging (NIA) can further improve mechanical properties especially the corrosion resistance of Al–Zn–Mg–Cu alloys. The reasons for the optimization of mechanical properties and corrosion resistance of Al–Zn–Mg–Cu alloys by NIA can be concluded in two aspects. Firstly, in the heating process of NIA, the alloy is heated to a temperature much higher than the conventional T6-temperature to make intergranular η′-phases spherical. Thus, the distribution of intergranular η′-phases is discontinuous, which improves the corrosion resistance. Secondly, during the subsequent cooling process, the continuously decreasing temperature is found to inhibit the coarsening of η′-phases and it also induces secondary precipitation of η′-phases. The fine secondary-precipitated η′-phases increase the precipitation density, which leads to the extra strength and ductility.

For Al–Cu–Mg–Si alloys with high Cu/Mg ratio, θ′-phases are the main strengthening phases [17] and they have good thermal stability [18]. On this account, during short-time and high-temperature aging,

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θ′-phases would not easily coarsen. What's more, the formation and growth of θ′-phase are the result of atomic diffusion controlled by heat activation. High temperature would promote its growth while low temperature inhibits its growth, thus the secondary precipitation of fine θ′-phases would also occur as temperature decreases. Therefore, NIA is suitable for the Al–Cu–Mg–Si alloys with high Cu/Mg ratio to improve their LCF properties. This is because that according to the dislocation slip reversibility [19], fine shearable precipitates tend to suffer from repeated dislocation cutting under cyclic loading, which restrains the dislocation piling up at the crack tip, decreases damage accumulation in the plastic zone and improves fatigue resistance.

To sum up, non-isothermal aging treatment will be an important heat treatment method for large Al–Cu–Mg–Si forgings. For one thing, the secondary precipitation of fine θ′-phases during NIA treatment would improve the ductility of the alloy without sacrificing strength, which solves the degradation of LCF properties due to the poor plasticity in T6 aged alloys. For another, NIA treatment including a heating and a cooling procedure does not require additional mechanical deformation. Thus, it is more suitable for the age-strengthening treatment of large die forgings than TMT treatment. Thirdly, compared with T6 and TMT treatments, the NIA process is more conducive to saving energy and improving production efficiency. Therefore, the aim of this study is to investigate the LCF behaviors of the Al–4.4Cu–0.69Mg–0.64Si alloys under isothermal (T6) and non-isothermal (NIA) aging. Particular attention is paid to the interactions between precipitates and dislocations and their influences on the fatigue damage mechanisms.

2. Materials and Experiments

The material used in this study is an Al–4.4Cu–0.69Mg–0.64Si–0.52Mn–0.12Fe (wt%) forging alloy. The alloy was solution-treated at 510 °C for 1 h, then quenched in water immediately, followed by isothermal (T6) and non-isothermal (NIA) aging treatment, respectively. The heat treatment procedures are shown in Fig. 1.

Room temperature tensile tests and low cycle fatigue tests were all carried out on a MTS 810 testing machine according to the ASTM E8 and ASTM E606 standard, respectively. The tensile tests were performed with an axial loading speed of 1 mm/min. The low cycle fatigue tests were performed with sinusoidal waveform loading with strain ratio (R) of −1 and a constant frequency of 0.5 Hz, and the specimens were tested with imposed strain amplitudes of 0.45%, 0.6%, 0.75% and 0.9%. The failure was defined as a 20% load drop or complete specimen separation, whichever occurred first. For both tensile and fatigue tests,

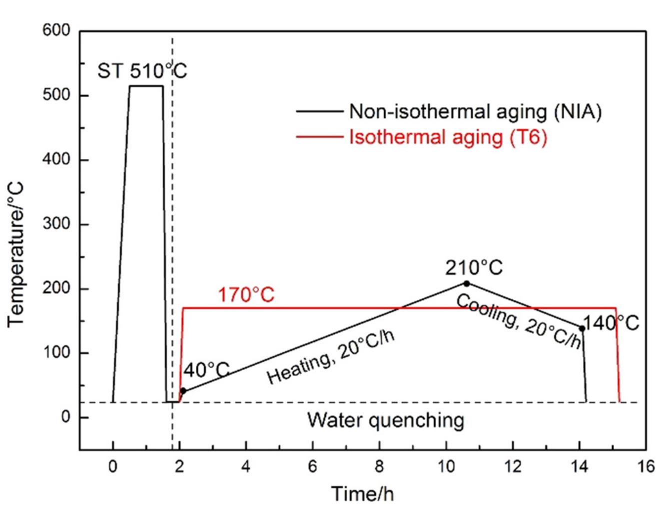

Fig. 1. Schematic diagram of solution (ST) and aging (T6, NIA) treatment.

three to five specimens were tested at each set of testing parameters. The geometry, dimensions of specimens, and the equipment used in the tensile and low cycle fatigue tests are shown in Fig. 2.

Microstructural and fractographic examinations of the Al–4.4Cu–0.69Mg–0.64Si alloy after LCF tests were carried out by scanning electron microscopy (SEM). The characterization of precipitates after aging and fatigue was performed on transmission electron microscopy (TEM/HRTEM). TEM foils were prepared after mechanical grinding to 0.08 mm, followed by twin-jet electrical polishing in a mixture of 30% nitric acid and 70% methanol at ~25 V and −30 °C.

3. Results

3.1. Tensile Properties

The room temperature tensile properties obtained from the parallel-samples under different aging conditions are listed in Table 1. It is notable that the T6 specimens display a mean yield strength (YS) of ~432 MPa, a mean ultimate tensile strength (UTS) of ~516 MPa and a mean elongation (El) of ~10.6%. Compared with the T6 specimens, the NIA specimens show a significantly higher mean YS of ~458 MPa and higher mean elongation of ~12.5%.

The work-hardening behaviors of the T6 and NIA specimens during tensile tests are analyzed by means of work-hardening rate, $\theta = d\sigma/d\varepsilon$, where σ and ε are the true stress and true strain in tensile tests [20]. Fig. 3 shows the work-hardening rate (θ) versus true strain (ε) curves for the T6 and NIA specimens. It can be seen from Fig. 3 that the work-hardening rate of the T6 specimen is slightly higher than that of the NIA specimen.

3.2. Cyclic Stress Response Behavior

The cyclic stress response behaviors of T6 and NIA specimens are analyzed by the variations of stress amplitudes (σ_a) and the mean stresses (σ_m) with respect to the number of cycles to failure (N_f) at different strain amplitudes as shown in Fig. 4. The corresponding data is from the specimen closest to the average fatigue life, where the average fatigue life is the average value of parallel-samples with fatigue-life fluctuations within 2% (in this paper, all LCF data for characterizing fatigue properties were obtained by this method). It can be found that with increasing strain amplitudes, the stress amplitudes increase and the fatigue lives decrease. Additionally, for T6 specimens, pronounced and continuous cyclic hardening is seen at all strain amplitudes investigated. While the NIA specimens are manifested as slight cyclic hardening behavior within the several beginning cycles (1 − 100) followed by cyclic stability until failure at all strain amplitudes investigated. Another noteworthy change is that the threshold cyclic stress amplitudes of NIA specimens are higher than those of T6 specimens at all strain amplitudes. For example, at strain amplitude of 0.6%, the stress amplitude of T6 specimen increases steady from 352.3 MPa up to 403.8 MPa while that of NIA specimen remains nearly constant at about 403 MPa after the initial increasing from the threshold value of 381.6 MPa. What's more, the mean stresses of all specimens are almost negative, which indicates that specimens during LCF tests undergo compressive mean stresses. The mean stress curves show a trend of rising first and then dropping, in other words, the compressive mean stresses decrease first and then increase in different degrees. For T6 specimens, the increase in compressive mean stress occurs in the early cycles before fracture, while for NIA specimens the increase in compressive mean stress arises only when fracture occurs. The rebuilding of the compressive mean stresses is caused by the initiation and the growth of macroscopic crack, thus the earlier it appears, the lower the crack initiation and growth resistances would be.