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Original Research

Aging behavior and fatigue crack propagation of high Zn-containing Al-Zn-Mg-Cu alloys with zinc variation☆

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ABSTRACT

In the present work, the influence of two-step aging treatments on hardness, electrical conductivity and mechanical properties of two high Zn-containing Al-Zn-Mg-Cu alloys with zinc content variation was investigated and the detailed T76 aging parameters were proposed. The microstructure of the precipitates were studied by transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HREM) and then quantitatively investigated with the aid of an image analysis. The fatigue performances were researched by the fatigue crack propagation (FCP) rate test and fracture morphology was observed with scanning electron microscopy (SEM). The results show that the matrix precipitate size distributions of both alloys had significant difference, so as to fatigue crack propagation rates and fracture appearance. The shear and bypass mechanisms of dislocation-precipitate interactions were employed to explain the difference. Among the shearable precipitates, the proportion of larger size precipitates for the higher zinc content alloy is bigger than that for the lower zinc content alloy. The coarse shearable precipitates hinder the propagation of the fatigue cracks, leading to inferior FCP rate. For both alloys, the shear mechanism possesses the dominant factor, finally causing a preponderance in the FCP resistance for the higher zinc content alloy than the lower one.

1. Introduction

The age-hardened Al-Zn-Mg-Cu aluminum alloys are widely used for aircraft structures and various critical military facilities due to their excellent combinations of strength, fracture toughness, stress corrosion cracking resistance and fatigue resistance, especially fatigue damage tolerance [1–3]. Based on the principles of aircraft design, the higher fatigue crack growth resistance of advanced aluminum alloys is required and gets much attention. In the past decades, fatigue properties of Al–Zn–Mg-Cu alloys are significantly investigated, with special emphasis on the influence of the microstructure (constituent particles [4,5], grain size [5–7], grain orientation [5,6] and precipitates [8–11]) on the fatigue crack propagation behavior. For the age-hardenable aluminum alloys, under the same service condition, the propagation path and growth rate of the fatigue crack are closely related to the matrix precipitates (MPt), grain boundary precipitates (GBP) and precipitate free zones (PFZ) adjacent to grain boundary [8,9].

Current researches on this subject have made great progress. Höppel et al. [12] find that the fatigue properties are significantly affected by matrix precipitate size. The size of precipitates in the over-aged alloy is larger than it in the peak-aged and under-aged alloy, resulting in lower fatigue limit and shorter fatigue life of the over-aged alloy. The interaction mechanisms between dislocations and precipitates also affect the fatigue properties. For the fine and coherent precipitates, dislocations can shear them and glide more-or-less reversibly during cyclic loading [9]. The study of Desmukh et al. [8] on aluminum alloys demonstrates that planar-reversible slip fosters fatigue crack growth resistance, leading to the decrease of fatigue crack growth (FCG) rate. The precipitates in the over-aged alloy have relatively large size and semi-coherent or incoherent with the parent phase, which cannot be sheared by dislocations. However, this allows the over-aged alloy to deform homogeneously, and as a result the over-aged alloy possesses a higher fatigue crack propagation threshold. Besides, the existence of precipitate free zones (PFZs) has a detrimental influence on the fatigue life and the decrease in the PFZ width brings about the increase in the fatigue life [8,13]. Chen et al. [11] assert that the effect of grain boundary precipitates and PFZ adjacent to the grain boundary on the crack growth resistance is not significant as compared

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with that of the precipitates inside grains. It is very difficult to separately analyze the function of each individual part, so the role of them still remains controversial and ambiguous. For the most part, a combination influence of these factors is treated as the reason accounted for fatigue properties [8,9].

However, a large proportion of emphases in the study of the aforementioned researchers are placed on investigations about the influence of precipitates under various aging conditions on fatigue properties. Few literatures have concentrated on associating main alloy composition adjustment with fatigue performance change. Such studies on the basis of Al-Zn-Mg-Cu alloys with the zinc content higher than 9.0 wt% are quite rare. So it is quite valuable to investigate the true effect of main alloying composition variation on fatigue properties.

In present work, two high Zn-containing Al-Zn-Mg-Cu alloys with the sole change in zinc content are investigated. The T76 aging treatments for both have been verified by hardness, conductivity and mechanical properties. The fatigue crack propagations of both alloys under T76 temper are studied. The difference on the precipitate characteristics and fatigue crack propagation between the two alloys is studied by transmission electron microscopy (TEM), high-resolution transmission electron microscopy (HREM), scanning electron microscopy (SEM) and fatigue crack propagation rate tests. The link among zinc content variation, precipitate characteristics and fatigue crack propagation rate is explored with the modes of dislocation-precipitate interactions.

2. Experimental procedure

2.1. Material and processing

The investigations were carried out on two extruded Al-Zn-Mg-Cu alloy plates with the chemical composition shown in Table 1. Two Al-Zn-Mg-Cu alloy plates were named as Alloy I and Alloy II for inferior and superior zinc content, respectively. The extruded plates had a shape of 100 mm in long transverse direction and 25 mm in short transverse direction. The specimens cut from extruded plates were appropriately solution heat treated and cold water quenched, followed by typical two-step aging treatments. The first step aging treatment schedule for the two alloys was aged at 110 °C for 8 h. According to previous research work, 160 °C was chosen as the second step aging temperature.

2.2. Performance test

The aging hardening processes were monitored by a 430SVD Vickers hardness tester using a loading force of 5 kgf and a dwelling time of 10 s. Each hardness datum of the samples was the mean value of ten indentations. The electrical conductivity of the specimens was measured using the WD-Z eddy current meter at room temperature with the same datum collecting techniques as the hardness. Samples for mechanical properties examination were cut from the plates paralleling to the rolling direction. All these tensile samples were cut from the plate core and prepared according to ASTM Standard E 517-00 with the gauge length parallel to the rolling direction. The tensile properties of the alloy under different aging times were measured by a WD3100 test machine at a constant speed of 2 mm/min. FCG tests were performed on a Servopulser fatigue test machine using compact tension [C(T)] samples according to ASTM E647 standard. Fig. 1 shows the geometry of the C(T) samples. The samples were machined from the plates in the longitudinal-transverse (L-T) direction, maintaining the crack propagation direction along the long transverse direction. Before the FCG rate tests, each C(T) sample was subjected to fatigue loading in order to obtain a pre-crack with the length of approximately 1.0 mm. Tests were conducted in air at room temperature, using a constant amplitude sinusoidal loading with a stress ratio of R=0.1 at a frequency of 10 Hz. The fatigue crack length measurements were carried out using the compliance method by employing a clip gauge at the notch mouth.

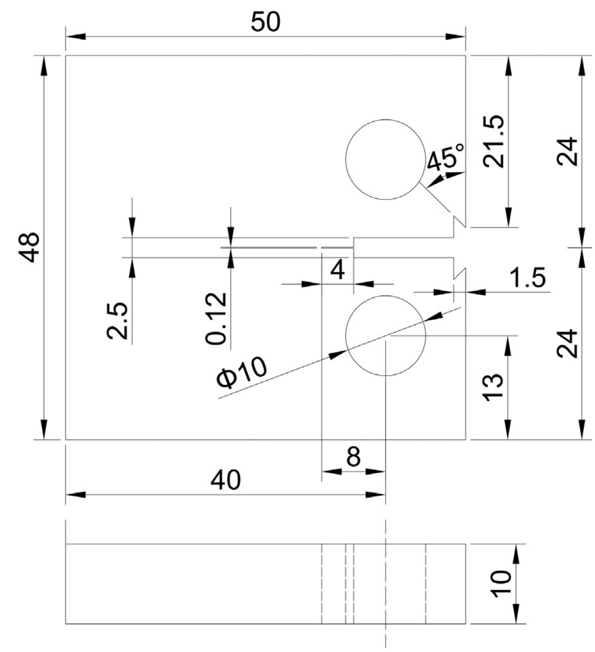

Fig. 1. Geometry of the C(T) samples (dimensions in mm).

Table 1
Chemical composition of the two aluminum alloy extruded plate (in wt%).

Element	Zn	Mg	Cu	Zr	Fe	Si	Al
Alloy I	9.32	2.00	1.76	0.15	0.052	0.033	Balance
Alloy II	9.78	2.04	1.76	0.11	0.056	0.034	Balance

2.3. Microstructure observation

TEM examinations were conducted on a JEOL JEM-2010 transmission electron microscope, operating at 200 kV. Three millimeter diameter disks for TEM observation were punched out directly from slices which were mechanically grounded down to 50 μm thickness. These disks were electro polished using a twinjet machine with a 25% nitric acid solution in methanol at −30 °C and 15–25 V. The microstructures and fracture surfaces of the samples were examined in detail using a field emission gun scanning electron microscope (FEG-SEM) JEOL JSM 7001F operating at 15 kV. Based on the SEM micrographs, the fatigue striations were measured by an image analysis to obtain striation spacing corresponding to different fatigue crack propagation stages.

3. Results and discussion

3.1. Hardness, conductivity and mechanical properties

The hardness and electrical conductivity curves of the investigated alloy aged 110 °C for 8 h and then preserved at 160 °C are shown in Fig. 2(a) and (b), respectively. Both of the two alloys exhibited a transitory increase in hardness at first and then a continuously steady decreased till the end. For Alloy I, it showed an increase in hardness during the first 4 h, followed by a more gentle decrease for up to 24 h. As for Alloy II, it took 2 h to approach a peak and then endured a more rapid decrease than that of Alloy I. The hardness peak for Alloy I to reach at 4 h was 216.7 HV while Alloy II took 2 h to reach a peak of 214.5 HV. At this 2 h, Alloy I owned a hardness value of 214.9 HV