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Effect of grain size on fatigue-crack growth in 2524 aluminium alloy

Deyan Yin [a,b], Huiqun Liu [a,b,*], Yuqiang Chen [c,*], Danqing Yi [a,b], Bo Wang [a,b], Bin Wang [a,b], Fanghua Shen [a,b], Shang Fu [a,b], Cong Tang [a,b], Suping Pan [a,b]

[a] School of Materials Science and Engineering, Central South University, Changsha, Hunan 410083, PR China
[b] Key Laboratory of Nonferrous Metal Materials Sciences and Engineering, Ministry of Education, Central South University, Changsha, Hunan 410083, PR China
[c] Hunan University of Science and Technology, Xiangtan, Hunan 411201, PR China

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ABSTRACT

In this study, industrial 2524 aluminium alloy plates with various grain sizes (0.8–298 μm) were prepared by cold rolling and heat treatment. The fatigue-crack-growth rate was studied as a function of grain size through fatigue tests and microstructural observations. The results showed that grain refinement led to a decrease in the resistance against fatigue-crack growth. Besides, the levels of crack closure in coarse-grained samples were higher than those in fine-grained ones at low values of the range of the stress intensity factor K, ΔK. This phenomenon was predicted and explained well by the crack-deflection model.

1. Introduction

Al–Cu–Mg (2000 series) aluminium alloys are widely used in aircrafts because of their outstanding damage-tolerance and fatigue-resistance properties. An excellent example is the 2524 alloy, which was developed by Alcoa in the 1990s and has been used as wing and fuselage skin on Boeing 777 and Airbus A380 [1–4]. The safety of an aircraft is closely related to the fatigue property of the alloy used. Earlier studies revealed that experimental conditions such as applied loading and environmental factors play significant roles on an alloy's fatigue properties [5,1,6,7]. However, recent studies indicated that intrinsic factors, including physical metallurgical properties, of the alloy have stronger effects on its fatigue properties [8–12].

Among the physical metallurgical properties, grain size is one of the most important factors. Grain size significantly influences both fatigue-crack initiation and propagation behaviour [13,14]. On the basis of previous work on microcrystalline metals (the grain sizes were typically above 1 μm) and ultra-fine-grained crystalline metals (the grain sizes were typically in the range of 100 nm to 1 μm), it is generally recognized that a structure with relatively larger grain size tends to have a higher fatigue-crack-growth threshold (ΔK_{th}) and lower crack-growth rate [14,15]. The increase in fatigue-growth resistance with larger grain size is attributed to the decrease in driving force of changes in the crack path, which is induced by the microstructure and possible contact between facets of rough cracks [16]. It is well known that this beneficial effect is typically more pronounced at a low range of the stress intensity factor K, ΔK, where both the size of cyclic plastic zones and the opening displacement of cyclic crack tips are smaller than the size of grains [17].

In order to study the effects of grain size on fatigue behaviour, researchers have obtained alloys with different grain sizes using different methods such as electrodeposition, equal-channel angular pressing, and cryomilling [18–22]. These methods have inevitably introduced different characteristics, such as dislocations and defects, which increase the complexity when comparing the effects of grain size on the fatigue behaviour of these alloys. Besides, as it is difficult to obtain sufficient number of large samples by these methods, some works have been conducted on non-standard samples, which might have affected the validity of the experiments. Therefore, it is important to obtain materials with significantly different grain sizes under the same processing conditions to examine their effects on the fatigue behaviour of the 2524 alloy.

In our present work, we successfully prepared 2524 aluminium alloy plates with widely varying grain sizes through conventional cold rolling and heat treatment. The fatigue-crack-growth behaviour of these plates was investigated in detail with a fatigue testing machine, an optical microscope, a transmission electron microscope (TEM), a scanning electron microscope (SEM), and a three-dimensional microscope. The aim of this work is to reveal

* Corresponding authors at: School of Materials Science and Engineering, Central South University, Changsha, Hunan 410083, PR China (H. Liu). Tel./fax: +86 731 88836320.
E-mail addresses: liuhuiqun@csu.edu.cn (H. Liu), yqchen1984@163.com (Y. Chen).

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the influence of grain size on the fatigue-crack-growth behaviour of 2524 aluminium alloy.

2. Materials and experimental methods

A commercial hot-rolled 2524 alloy plate with thickness of 6 mm was provided by Southwest Aluminium Co. Ltd., China. Its nominal composition was 4.2% Cu, 1.41% Mg, 0.56% Mn, 0.08% Fe, 0.06% Si (in wt.%), and the balance was Al. The processing and heat-treatment parameters of plates with four different grain sizes (sample 1, sample 2, sample 3, and sample 4) are listed in Table 1.

Tensile tests were carried out on a CSS-4400 testing machine along the transverse (T) direction. Fatigue-crack propagation and crack-closure tests were carried out on an 250-kN fatigue machine (8803, Instron, USA) using the middle-tension sample M(T) (see Fig. 1). Specimens were taken from alloy plates along the T direction and pre-cracked under mode-I. A sinusoidal loading was applied at a frequency of 10 Hz and load ratio of 0.1. The length of the fatigue crack was measured by an optical microscope (±1 μm) attached on the fatigue machine. The following equation was used to determine the stress intensity factor:

$$\Delta K = \frac{\Delta P}{B}\sqrt{\frac{\pi\alpha}{2w}\sec\frac{\pi\alpha}{2}}, \quad (1)$$

where P is the load (in MPa); B and w are the thickness (in cm) and width of the sample, respectively; a is the crack length (in cm); and $\alpha = 2a/w$.

The morphology of the fracture surface on each sample after cyclical deformation was observed by a three-dimensional microscope (Kh7700, Hirox, Japan). Metallographic specimens were prepared in a standard procedure and etched in a solution consisting of HF (2 mL), HCl (3 mL), HNO_3 (5 mL), and H_2O (200 mL). The microstructure was observed by multifunction optical microscopy and using an SEM (JSM-5600LV, JEOL, Japan). The microstructure of some samples was characterized by a TEM (TecnaiG2 20, FEI, USA) operating at 200 kV. Disks with diameters of 3 mm were cut from fatigue-tested samples for TEM observation. These disks were first ground to a thickness of 0.1 mm and then double-jet polished electrolytically in a solution of 33% HNO_3 and 67% methanol at −30 °C.

3. Results

3.1. Grain structure and tensile properties

The microstructures of the 2524 aluminium alloy samples with different grain sizes (samples 1, 2, 3 and 4) were characterized by TEM and OM, as shown by the results in Figs. 2 and 3, respectively. The average measured grain sizes of the four samples are shown in Table 2. The mean grain size of sample 1 was about 0.8 μm, which was associated with the low-density dislocation and without precipitates at the interior of the grains. The grain structures of samples 2 and 3 were relatively equiaxed; the measured grain size of sample 2 was 25, 16, and 29 μm in the longitudinal (L), short transverse (S), and T directions, respectively; the grain size of sample 3 was 59, 46, and 66 μm in the L, S, and T directions, respectively. The grain structure of sample 4 was the most coarse, with grain sizes of 324, 298, and 345 μm in the L, S, and T directions, respectively. As shown by their tensile properties, listed in Table 3, the four samples obeyed the Hall–Petch relationship and clearly revealed the effect of strengthening by grain refinement. For example, sample 1, which had ultra-fine grains, had a higher ultimate strength of 500 MPa, while the strength decreased for samples with larger grain sizes.

Table 1
The processing and heat treatment routes of 2524 alloy plate samples.

Samples	The processing and heat treatment routes
Sample 1	6 mm hot rolled plate → solid solution (500 °C/1 h) → cold rolling to 1.2 mm → annealing (380 °C/1 min) → 1–2% pre-deformation before natural aging for 96 h
Sample 2	6 mm hot rolled plate → cold rolling to 3.6 mm → solid solution (500 °C/30 min) → cold rolling to 1.2 mm → solid solution (500 °C/30 min) → 1–2% pre-deformation before natural aging for 96 h
Sample 3	6 mm hot rolled plate → cold rolling to 1.2 mm → annealing (330 °C/30 min + 380 °C/30 min + 420 °C/30 min) → solid solution (500 °C/1 h) → 1–2% pre-deformation before natural aging for 96 h
Sample 4	6 mm hot rolled plate → eight passes cold rolling with 10% reduction for each pass, and intermediate annealing (330 °C/30 min + 380 °C/30 min + 420 °C/30 min) after each rolling pass → solid solution(500 °C/1 h) → 1–2% pre-deformation before natural aging for 96 h

3.2. Fatigue-crack-growth rate and fatigue-crack closure

The curves of the fatigue-crack-growth rate versus ΔK (the applied stress intensity factor range) for the four samples are plotted in Fig. 4. Sample 1 exhibited higher fatigue-crack-growth rates with ultrafine grain size (0.8 μm). With increases in grain size, ΔK_{th} increased and the fatigue-crack-growth rate decreased significantly, especially in the region near ΔK_{th}. When $\Delta K > 27$ MPa $m^{1/2}$, the fatigue-crack-growth rates of samples 2, 3, and 4 were almost the same. Since the grain size effect on fatigue crack propagation is more obvious under low ΔK, thus the following analyses focus on the regime $\Delta K < 27$ MPa $m^{1/2}$.

The crack-closure results of the four samples are shown in Fig. 5 in terms of $\Delta K_{eff}/\Delta K$ and Fig. 6 in terms of K_{op}/K_{max}, where $\Delta K_{eff} = K_{max} - K_{op}$ is the effective stress intensity factor, K_{max} is the maximum stress intensity level, and K_{op} is the stress intensity level measured at the onset of closure. It can be seen that ΔK_{eff} of sample 1 had a higher value than those of the other three samples. The value of ΔK_{eff} decreased with increases in grain size, which implies that sample 1 with finer grains had higher fatigue-crack-growth rate than those with coarser grains. This is attributed to the higher closure level for larger grains at low ΔK levels (i.e. increasing $\Delta K_{eff}/\Delta K$ and decreasing K_{op}/K_{max}).

3.3. Fatigue-crack fracture

Three-dimensional reconstructions of the fracture-surface morphology of four samples at $\Delta K = 12$ MPa $m^{1/2}$ are shown in Fig. 7. Line profile of these fracture surfaces were drawn according to the method in ref. [23].

The standard deviation of asperity heights (σ_0) is often used to quantify the surface roughness, which is given as followings [24]:

$$\sigma_0 = \left[\frac{\sum_i^n z_i}{n-1}\right] \quad (2)$$

wherein z_i is the height of asperity and n is the total number of asperities.

A statistical work on the asperity height was carried out and the standard deviations of asperity heights (σ_0) for four samples were calculated to be 3.5 μm, 10.3 μm, 27.3 μm and 68.6 μm, respectively. It reveals that the fracture-surface roughness increases significantly with the increase of grain size. σ_0 value of sample 4 is almost 20 times greater than that of sample 1. But the fracture-surface roughness increases with the grain size is apparently non-linear, since the grain size of sample 4 is about 300 times than that of sample 1.