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Influence of grain structure and crystallographic orientation on fatigue crack propagation behavior of 7050 alloy thick plate

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ABSTRACT

Fatigue crack propagations of 7050 alloy thick plate in different orientations were investigated. Anisotropy of fatigue property showed some difference compared to that of strength and toughness. Microstructural observations revealed that the anisotropy was significantly influenced by structure and orientation characteristics of recrystallized grains. Detailed analysis based on crystallographic model and Schmid factors suggested that the fatigue behaviors, including inter/transgranular propagation, crack deflection or bifurcation, depend on crystallographic orientations and geometry of local microstructure, particularly the tilt and twist angle differences of slip planes or crack planes, together with cooperation and competition between movement of slip systems and loading stress.

1. Introduction

Al–Cu systems(2xxx series) and Al–Zn–Mg(–Cu) systems(7xxx series) alloys have been widely used in aircraft manufacturing industry due to their good mechanical properties and low densities [1,2]. Based on security considerations, damage related properties such as fracture toughness and fatigue are important to these materials working in complex environment with long hours [3]. For decades, improvements on damage resistance have been longstanding objective to material scientists. Due to the complex process and disastrous consequence, investigations to fatigue failure attract the most attention [4]. However, substantive consequence of Al–Zn–Mg(–Cu) systems alloy is insufficient and less than Al–Cu systems alloy. Moreover, the knowledge gained in the latter cannot readily be extrapolated to the former due to their differences in phases and strengthening mechanisms [5,6]. Consequently, more efforts are needed to understand the fatigue mechanism in Al–Zn–Mg(–Cu) systems alloy.

As one typical Al–Zn–Mg(–Cu) alloys, 7050 alloy was chosen in this work because of its widespread use based on excellent integrated performance of high strength, fracture toughness and stress corrosion resistance. Moreover, it possesses relatively small quench sensitivity by adding zirconium element, thus 7050 alloy is suitable to manufacture components in larger-scale, i.e. thick plate and heavy forging. Nowadays, Al–Zn–Mg(–Cu) alloy thick plates have been well welcomed in aviation industry, because they enable aircraft to apply monolithic component instead of assembly parts which need welding or riveting. However, researches showed that Al–Zn–Mg(–Cu) alloy thick plates are highly anisotropic in nature [7]. Anisotropy of strength, fracture toughness, fatigue or corrosion property was found to exist in these aluminum alloy products. From a practical viewpoint, it is meaningful to observe the fatigue anisotropy effect of 7050 alloy thick plates. In fact, it is now widely acknowledged that these anisotropies are closely related to microstructural characteristics, such as grain structure, macro- or micro-texture and constituents [7–9]. As a result, the development and optimization of these aluminum alloy plates are based on a well understanding to the influence of microstructure.

In recent decades, researches on the role of microstructure to damage behavior have received lots of attention. Vasudevan et al. [10] pointed out that the considered microstructural variables are grain size, precipitates and stacking fault energy. The influence of grain structure and slip characteristics in aluminum alloys were highlighted by Suresh et al. [11]. Researches by Chen et al. [12] revealed that grain boundary and grain orientation can greatly affect the local crack propagation behaviors. Although microstructure is found to affect the fatigue behavior, the correlation between fatigue behavior and grain structure factors have not been clearly understood. Some microstructure-based models have been developed, intending to describe fatigue crack growth behaviors.

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Zhai et al. [13] proposed a crystallographic model for fatigue crack by taking into account both crack-plane twist and tilt effects. Kamp et al. [14] constructed a semi-quantitative relationship between crack path and microstructure. Among these researches, it is worth to note that the factors such as grain orientation and characteristic of grain boundary could play crucial roles and must be further investigated.

From an experimental viewpoint, microstructure-based researches on fatigue crack propagation process depend on microstructural observation methods. The electron back scattering diffraction (EBSD) technology has been extensively accepted as a suitable method which can quantify the crystallography of grain, crack path and grain boundary. By using EBSD technology, features of fatigue cracks have been successfully characterized for titanium alloys [15,16], aluminum alloys [12,17,18], steel [19,20], etc.

Therefore, the purpose of this work is not only to acquire the basic fatigue properties, but also to perform a detailed analysis on crack propagation process from macroscopic and crystallographic aspects. The influences of grain structure and crystallographic orientation on fatigue crack propagation rates were discussed in detail, aiming to develop a better fatigue resistance to these alloy thick plates.

2. Experimental procedures

The material used in this study was 200 mm thick 7050-T7451 aluminum alloy plate with nominal composition of 6.67%Zn, 2.43%Cu, 2.19%Mg, 0.1%Zr, 0.1%Fe, 0.1%Si and Al as rest (all in wt%).

The schematic of sampling is shown in Fig. 1. According to ASTM E399 and E647 standard respectively, plan strain fracture toughness and fatigue crack growth test were performed on compact tension samples in three orientations, namely L–T, T–L and N–T (L, longitudinal rolling direction; T, transverse direction; N, normal direction). For each sample, the loading direction was parallel to the direction preceding the hyphen, and the crack propagation direction was parallel to the direction following the hyphen. Tensile properties were measured on samples parallel to the three loading orientations of fatigue tests, respectively abbreviated as L, T and N. All the samples were machined down at the 1/2 thickness of the plate. The tensile tests, fracture toughness tests and fatigue tests were all carried out on a servo hydraulic MTS 810 test machine at room temperature in laboratory air. Fatigue crack growth tests were measured under conditions of increasing applied stress intensity factor range, $\Delta k = K_{max} - K_{min}$, with crack extension under a constant tension–tension cyclic loading with ratio of $0.1 (R = \sigma_{min}/\sigma_{max})$. Fig. 2 shows the major dimensions of samples used in the fatigue tests.

Microstructural observations were performed on metallographic planes parallel to the fatigue fracture surfaces as shown in Fig. 1 with dashed line. The corresponding metallographic planes for L–T, T–L and N–T samples were respectively cross plane, longitudinal plane and rolling plane of the thick plate. Metallographic samples were prepared using a conventional mechanical polishing followed by etching with Graff Sargent solution (1 mL HF, 16 mL HNO_3, 3 g CrO_3, 83 mL H_2O). The morphologies of fatigue fracture surfaces were observed on Sirion 200 scanning electron microscopy (SEM). To identify the crystallographic relationship, interrupted fatigue test was carried out to achieve unfaulted sample. Fatigue crack path images on the crack profile were collected by an EBSD system attached to SEM. The step size between points on the scan grid was set to 1 μm. TSL OIM 5 software was used to index and further analyze these data.

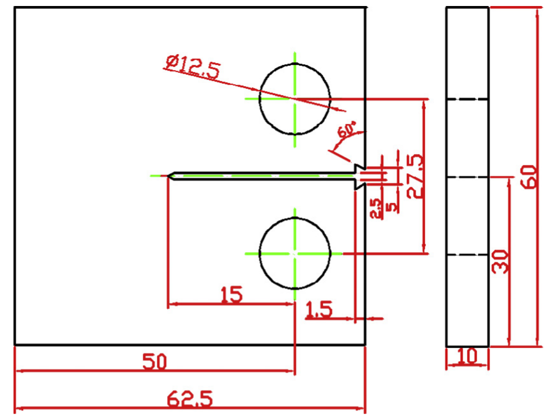

Fig. 2. Dimensional details of the fatigue sample (dimensions in mm).

3. Results and discussion

3.1. Tensile, fracture toughness and fatigue crack growth results

Table 1 shows the tensile properties and fracture toughness of experimental thick plate in three orientations. It can be seen that the values of tensile strength, yield strength and elongation are all ranked in the order L > T > N. Such differences are more obvious for the yield strength and elongation. While for the fracture toughness, sample in L–T orientation showed much higher K_{IC} than that in T–L and N–T orientation.

Fatigue crack growth curves for L–T, T–L and N–T sample are shown in Fig. 3. From a whole perspective, L–T sample exhibited relatively better fatigue performance than the other two orientations. At the near threshold region with ΔK lower than 10 MP$\sqrt{}$m, N–T sample showed a higher growth rate than L–T and T–L samples. However, as the ΔK increasing, the fatigue crack growth rate of T–L sample had a rapid increase. Especially at the medium and high ΔK regions, the fatigue crack growth rate of T–L sample was evidently higher than the other two directions. In contrast, the crack growth rate of N–T sample tended to slow down at the steady propagation stage. At the final stage of fatigue crack extension, the crack in N–T sample propagated faster than L–T sample, but still slower than T–L sample.

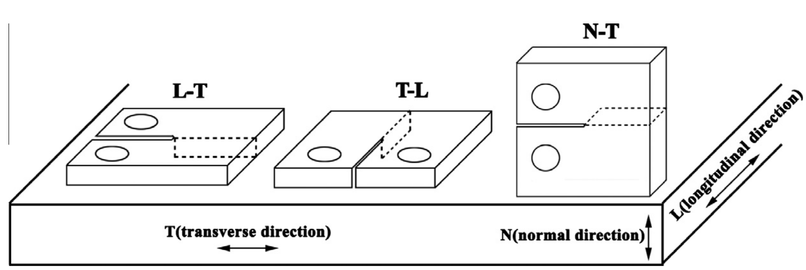

Fig. 1. Schematic diagrams showing the sample orientations and microstructural observation surfaces (in dashed line).