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Fatigue life prediction of laser welded 6156 Al-alloy joints based on crack closure

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ABSTRACT

The median *S–N* curves for laser beam welded 6156 Al-alloy butt joints and T-joints and crack growth rate curves for the base material were determined by fatigue experiments at stress ratio $R = 0.5$, 0.06, -1, respectively. The results showed that the fatigue strength of 6156 Al-alloy butt joint is obviously higher than that of T-joint. The fatigue limit and the crack growth threshold were proposed to determine the initial crack size for butt joint and T-joint. A fatigue life prediction approach based on crack closure was proposed, which can take into account the effect of welding residual stress. The predicted lives using the proposed approach agreed well with the experimental results.

1. Introduction

In recent years, aluminum alloy has been applied in more and more areas because of the superiorities such as low weight, high strength, and excellent resistance to corrosion compared to other materials. Welding is an economical and feasible manufacturing method and can be used in the cases where integral component is impossible to be manufactured by other production methods. Laser welding has been used widely in the industry because of its advantages such as narrow heat affected zone, small distortion and relatively high welding speed. The 6056 aluminum alloy is an alloy which exhibits an excellent compromise on corrosion resistance and high strength and particularly suitable for fuselage panels. The 6156 Al-alloy, which is the improved generation of 6056 Al-alloy, not only retains the excellent properties of 6056 Al-alloy but also increases the damage tolerance property. Laser beam welded structures of 6156 Al-alloy may be used for the fuselage panels in the future.

Welds are often the weakest portions of structures and fatigue failure is the most frequent failure mode. Much investigation has been conducted in the fatigue assessment of welded structures [1–4]. Nominal stress method, structural stress method, local stress method and fracture mechanic method are the four main fatigue assessment methods for welded joints. In many fields, the nominal stress method is still prevailing. This method requires the definition of the nominal stress and its permissible value for a classified structural detail. However, the nominal stress method is not applicable in case of more complex structural details because neither nominal stress nor permissible value can be assigned.

In general, total fatigue life consists of crack initiation life and crack propagation life. However, welding defects are inevitably introduced during fabrication. Metallurgical examinations show that the average depth of these flaws is 0.15 mm and typically the maximum depth is approximately 0.4 mm [5,6]. A review by Grover [7] suggested that even high-quality welds contain flaws up to a depth of about 0.1 mm. Initial crack-like defect depths of about 0.01–0.12 mm [8] 0.02–0.15 mm [9] or 0.01–0.4 mm [10] were observed in other previous works on fatigue of welded joints. These welding defects can eliminate the crack initiation stage of fatigue and the fatigue life of a welded joint is predominantly controlled by the crack propagation process [11]. This makes the fracture mechanics method suitable for the life prediction of weld joints.

Numerous equations have been developed to relate fatigue crack growth rate to the stress intensity factor range ΔK. The Paris-Erdogan [12] law is commonly accepted among the developed equations and given as:

$$da/dN = c(\Delta K)^m \tag{1}$$

where da/dN is the crack growth rate, and c, m are material constants.

The traditional fracture mechanics approach [13,14] calculates the fatigue lives of weld joints by integrating the Paris-Erdogan law between the initial crack size which can be given by the max-

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imum crack-like defect and the critical size corresponding to failure:

$$N = \int_{a_0}^{a_f} \frac{1}{c\Delta K^m} da \tag{2}$$

where a_0 is the initial crack size, and a_f is the critical crack size.

However, the crack growth rate is related to the stress ratio, and single constants c and m are unable to take into account the effect of stress ratio on crack growth. Moreover, the residual stress is inevitable during the welding process, but it is not taken into account in the traditional fracture mechanics approach.

The concept of crack closure proposed by Elber [15] has extensively been employed in describing the effect of stress ratio on fatigue crack growth. In the concept of crack closure, the fatigue crack growth drive force is the effective stress intensity factor range ΔK_{eff}, which can be calculated by the following expression:

$$\Delta K_{eff} = K_{\max} - K_{op} \tag{3}$$

where $K_{\max}$ is the maximum stress intensity factor, K_{op} is the stress intensity factor when the crack is fully open. The Paris-Erdogan law can then be written as:

$$da/dN = c_1(\Delta K_{eff})^{m_1} \tag{4}$$

The objective of the present work is to develop a fatigue life prediction approach based on crack closure, which can take into account the effect of welding residual stress for laser beam welded Al-alloy joints. Fatigue crack growth experiments for the base material and S–N curve tests at stress ratio $R = 0.5$, 0.06, -1, respectively, were first conducted for 6156 Al-alloy laser beam butt joints and T-joints. And then the initial crack sizes for both joint types were determined by the proposed method based on fatigue limit and crack growth threshold. Finally, the fatigue lives were predicted by the proposed approach for 6156 Al-alloy laser beam butt joints and T-joints.

2. Experiments

2.1. S–N curves tests

S–N curves tests were carried out on high-frequency fatigue testing machine using a sinusoidal waveform at a frequency of greater than 50 Hz. The specimens of the laser beam welded butt joint and T-joint for the S–N curve tests are shown in Fig. 1. The chemical composition of 6156-T4 aluminum alloy is listed in Table 1. The median S–N curves at $R = 0.5$, 0.06, -1, as shown in Fig. 2, were obtained using three stress levels. Tests for each stress level contained at least 4 effective specimens. The results are listed in Tables 2 and 3. The constants m and C for the median S–N curves ($\sigma_{\max}^m N = C$) at different stress ratios were listed in Table 4.

After failing the specimens, one fractured specimen was chosen for each stress level to conduct SEM analysis. No obvious discrepancy was found in the fractographs at different stress level for both butt joints and T-joints. A typical fractograph of fractured joints is shown in Fig. 3. It can be found that the crack initiated from weld toe due to high stress concentration and propagated along plate thickness direction as an approximate semi-elliptical aspect. So a surface semi-elliptical crack was assumed for both butt-joints and T-joints during the fatigue crack growth process.

2.2. Crack growth experiments

The crack growth experiments for the base material with the centre crack tension (CCT) fatigue crack growth specimens were also conducted at $R = 0.5$, 0.06, -1 following the standard ASTM E647-11 [16]. The experiments were carried out on MTS fatigue test system using a sinusoidal waveform at a frequency of 10 Hz.

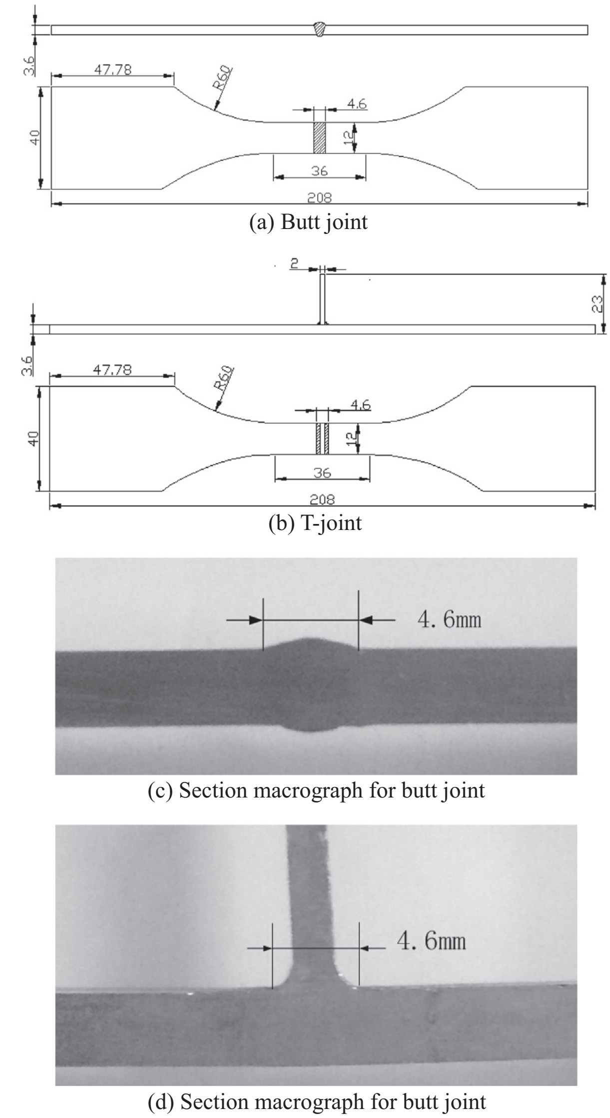

Fig. 1. Fatigue test specimens (dimensions in mm).

Table 1
Chemical composition (wt.%) of the base material.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
0.7	0.084	1.04	0.43	0.82	<0.05	0.15	Bal

For the crack growth test involving compressive loads ($R = -1$), an anti-buckling guide was used to avoid the specimen any buckling during the testing process. The experimental results are showed in Fig 4.

2.3. Fatigue limit tests

Median fatigue limits at $R = 0.5$ for the welded joints were tested by up-and-down method. The results were shown in Fig. 5. The median fatigue limits $\Delta\sigma_e$ at $R = 0.5$ were determined as 82 MPa and 55 MPa for butt joint and T-joint, respectively.

2.4. Residual stress measurement

The transverse residual stress (parallel to loading direction) at the middle of the specimen width was measured by X-ray method.