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Fatigue life prediction based on crack closure for 6156 Al-alloy laser welded joints under variable amplitude loading

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ABSTRACT

A fatigue prediction approach is proposed using fracture mechanics for laser beam welded Al-alloy joints under stationary variable amplitude loading. The proposed approach was based on the constant crack open stress intensity factor in each loading block for stationary variable amplitude loading. The influence of welding residual stress on fatigue life under stationary variable amplitude was taken into account by the change of crack open stress intensity factor in each loading block. The residual stress relaxation coefficient $\beta = 0.5$ was proposed to consider the residual stress relaxation for the laser beam welded Al-alloy joints during the fatigue crack growth process. Fatigue life prediction results showed that a very good agreement between experimental and estimated results was obtained.

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 cases where an integral component is impossible to be manufactured by other production methods. Laser beam welding has been applied widely in the industry due to 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. As its improved generation, the 6156 Al-alloy, except retaining the excellent properties of 6056 Al-alloy, raises 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. Moreover, most of the structures are subjected to random or variable amplitude loading. It is valuable to give accurate fatigue life prediction for welded joints under variable amplitude loading. The conventional fatigue prediction approach for welded structures under variable amplitude loading is based on S–N curve and cycle counting method combined with Miner's rule. The approach needs the S–N curve for the joints which can be obtained from the classified structural details in the design code (for instance, the IIW recommendations [1]). However, this approach is not applicable for more complex structural details because no classified structural detail 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. Weld toe flaws are particularly significant and metallurgical examinations of arc welds in steel [2,3] showed that their average depth was 0.15 mm and the maximum typically 0.4 mm. A review by Grover [4] suggested that even high-quality welded steel joints contain weld toe flaws up to a depth of about 0.1 mm. Initial crack-like defect depths of about 0.01–0.12 mm [5], 0.02–0.15 mm [2] or 0.01–0.4 mm [6] were observed in other previous works on fatigue of welded steel joints. These welding defects can eliminate the crack initiation stage and the fatigue life of a welded joint is predominantly controlled by the crack propagation process [7]. Therefore, the emphasis of the fatigue assessment for the welded structures should be focused on the crack growth portion of fatigue life, which can be assessed using the linear elastic fracture mechanics.

The problem becomes more complicated in the fatigue life prediction for welding joints using fracture mechanics under variable amplitude loading. In order to give a more accurate prediction, two factors have to be taken into account. The first one is the loading

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sequence effect; the second one is the influence of welding residual stress on fatigue crack growth.

The concept of crack closure proposed by Elber [8] has extensively been employed to explain the loading sequence effect in crack growth. In the concept of crack closure, the fatigue crack growth drive force is the effective stress intensity factor (SIF) range ΔK_{eff}, which can be calculated by the following expression:

$$\Delta K_{eff} = K_{max} - K_{op} \quad (1)$$

where K_{max} is the maximum SIF for a loading cycle, K_{op} is the SIF when the crack is fully open. The relation between crack growth rate da/dN and ΔK_{eff} can be expressed as:

$$da/dN = c(\Delta K_{eff})^m \quad (2)$$

In the present work, the fatigue crack growth behavior of 6156 Al-alloy laser beam welded butt joint and non-load carrying transverse attachment is investigated under variable amplitude loading. On the basis of crack closure, a fatigue life prediction approach is proposed for laser beam welded Al-alloy joints under stationary variable amplitude loading. The approach can take into account the effect of residual stress on the fatigue crack growth.

2. Experiments

2.1. Fatigue life tests

The specimens of the laser beam welded butt joint and non-load carrying transverse attachment for fatigue life tests are shown in Fig. 1. The tests were conducted on MTS fatigue test system using a sinusoidal waveform. The chemical compositions of the base material (6156-T4 aluminum alloy) and the welding wire (ER4047 Al–Si alloy) are listed in Table 1. The yield strength and ultimate tensile strength of the base material are 230 MPa and 341 MPa, respectively. The transverse residual stress (parallel to loading direction) at weld toe was measured by X-ray method for the joints. The results are −70.74 MPa for butt joint and 17.88 MPa for non-load carrying transverse attachment at the middle of specimen width, respectively. The spectrum loading sequence used in the present investigation is shown in Fig. 2, and listed in the Appendix. The total number of reversals in the sequence is 1000. Fatigue lives for both types of joints under different mean stresses S_{mf} which is the stress corresponding to 1g were tested. In order to ensure the actual loading reaching the specified loading, variable frequency control (1–10 Hz) was adopted in the fatigue life tests. The experimental results are listed in Table 2 and shown in Fig. 3.

After failure, some fracture surfaces were examined in a scanning electron microscope. A typical fractograph of a failed joint is shown in Fig. 4. It can be seen that the crack initiated at the weld toe and propagated through the plate thickness with an approximate semi-elliptical shape. Consequently, this crack front shape was assumed in the later analysis of fatigue crack growth in laser beam welded joints.

2.2. Fatigue crack growth tests

The crack growth experiments were performed on base metal center crack tension (CCT) specimens at $R = 0.5$, 0.06 and −1 at a frequency of 10 Hz, in accordance with ASTM E647-11 [9], on a MTS fatigue test system using a sinusoidal waveform. For the crack growth test involving compressive loads ($R = -1$), an anti-buckling guide was used to prevent the specimen from buckling during the tests. The experimental results are shown in Fig 5. The corresponding pairs constants c and m ($da/dN = c(\Delta K)^m$) for the base material at $R = 0.5$, 0.06 and −1 were listed in Table 3.

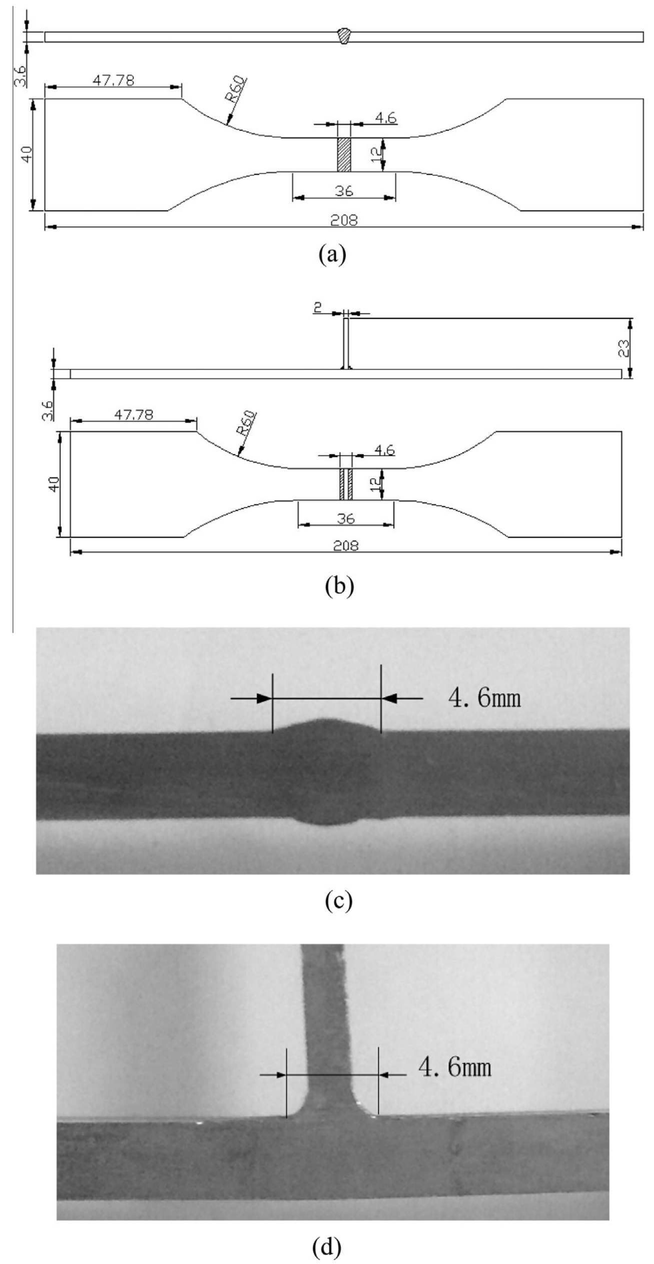

Fig. 1. Fatigue test specimens (dimensions in mm): (a) Butt joint, (b) non-load carrying transverse attachment, (c) section macrograph for butt joint and (d) section macrograph for non-load carrying transverse attachment.

Table 1
Chemical compositions (wt.%) of base metal and welding wire.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
6156	0.7	0.084	1.04	0.43	0.82	<0.05	0.15	Bal
ER4047	11.52	0.20	<0.001	0.01	0.01	–	0.001	Bal

2.3. Fatigue limit tests

Fatigue limits at $R = 0.5$ for the welded joints were tested by the staircase method, in accordance with BS IOS 12107-2003 [10], on a high-frequency fatigue testing machine using a sinusoidal waveform at a frequency of greater than 50 Hz. The results were shown in Fig. 6. The fatigue limits $\Delta\sigma_e$ at $R = 0.5$ were determined as 82 MPa and 55 MPa for butt joint and non-load carrying transverse attachment, respectively.