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Fatigue and fracture behaviour of friction stir welded aluminium–lithium 2195

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ABSTRACT

Aluminium–lithium (Al–Li) alloys offer attractive properties for lightweight aerospace structures, due to their low density, high strength and fatigue crack growth resistance. Although there are many advantages with Al–Li alloys, limitations remain while using conventional joining techniques.

Friction stir welding is a well-established solid-state joining process that is expected to reduce many of the concerns about Al–Li welding.

The work presented in this paper involves the characterisation of the fatigue performance of the AA2195-T8X at room temperature. SN and crack growth tests of base material and friction stir welded 5 mm thick specimens were performed. During crack growth tests, three different *R* ratios (minimum remote stress/maximum remote stress), 0.1, 0.5 and 0.8, were used per each three different material conditions: base material, heat affected zone (HAZ), and weldment. M(T) specimens containing notches at the centre of the weld, at the HAZ and at the base material, were tested. The fatigue crack growth specimens were left with an un-cracked ligament for final evaluation of fracture toughness.

Novel results are presented for fatigue crack growth and toughness on T–L orientation. The results for SN fatigue behaviour, fatigue crack growth and toughness of the studied alloy and its friction stir weldments present high values when compared with data found in the literature.

1. Introduction

In the aeronautics and space industries one of the most effective ways to reduce weight is to reduce the density of the aluminium alloys used. For purposes of reducing the alloy density, lithium additions have been used. The rapid increase in solid solubility of lithium in aluminium over the temperature range of 0–500 °C results in an alloy system achieving, through precipitation hardening, good strength levels. However, the addition of Li–Al alloys presents problems, as possible decreases in ductility and fracture toughness, delamination problems and poor stress corrosion cracking resistance. Increased strength with only minimal or no decrease in toughness is therefore a major issue [1,2].

The interest in Al–Li alloys derives from the large effect that lithium additions have on the modulus of aluminium, a 6% increase for every weight% added, and the density, a 3% decrease for every weight% added [3]. These changes apply for lithium additions up to 3 weight%. There have been three early generations of Al–Li alloys, (i) those produced in the 50s–70s, including alloys 2020 and 1420; these alloys experienced ductility and fracture toughness problems, or were of relatively low strength; (ii) those produced in the 1980s, including alloy 2090, 2091, 8090, and 8091, with high modulus and low density, but displaying anisotropic mechanical properties, and (iii) more recent high-strength alloys as the 2195 and 2198 alloys [4–6].

Al–Li alloys offer attractive properties for lightweight aerospace structures, due to their low density, high strength and fatigue crack growth resistance. Although there are many advantages with Al–Li alloys, limitations remain while using conventional joining techniques, as low joint efficiency (ratio of weld strength to base metal strength) in the as welded condition [7]. Post-weld heat treatment enhances the yield strength, but no increase in fatigue strength was observed by [8] in GTA welded AA2195 samples. Friction Stir Welding (FSW) is a well-established solid-state joining process, comprehensively reviewed in [9–11], that is expected to reduce many of the concerns about Al–Li welding.

The present work was performed under the ESA TRP 'Damage Tolerance of Cryogenic Pressure Vessels' aiming at defining potential applications for state of art FSW techniques in cryogenic tanks for Expendable Launch Vehicle and Reusable Launch Vehicle.

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2. SN fatigue tests

SN and fatigue crack growth tests of base material and friction stir welded (FSW) 5 mm thick specimens of the AA2195-T8X were performed at room temperature (RT). The test results of each specimen were linked to the specimen designation of the cut-off plan [12].

The AA2195 alloy was received in the T3R78 condition with an initial thickness of 6.35 mm and aged to T8X condition to obtain higher strength. The plates were machined to 5 mm thickness as a typical weld thickness in cryogenic launcher applications. More detailed information can be found in [13].

FSW, performed by MT-Aerospace, was optimised in order to obtain high strength and good ductility. The main parameters analysed in the optimisation procedure were the rotation speed, the travel speed, and the vertical down force. The selection criterion for the final weld was a flawless visual appearance of the weld, a high strength of the weld, a high angle of bending without cracking in bending tests and the lack of cleavage planes on the fracture surface of tensile and bending specimens. With the optimised parameters obtained, about 20 m of weld were prepared close to application conditions. As post-weld treatment only hand scraping technique was applied to remove sharp flash on the side of the weld. Welding direction is parallel to the material rolling direction, and loading is perpendicular to the weldment.

Preliminary tensile tests were performed in order to obtain the strength values of the AA2195-T8X friction stir welded material. These values, presented in Table 1, are used for the definition of the load levels of the fatigue tests and to determine the maximum load to be used on the fatigue pre-cracking and crack propagation procedures to prevent plasticity effects.

2.1. Test definitions

The stress life curves were evaluated according to ASTM [14,15] using integral specimens perpendicular to the weld. The specimen geometry is presented in Fig. 1 [12].

For the calculation of the maximum loads to be applied in SN tests, the initial section is considered to be $5 \times 12 = 60\ \text{mm}^2$, and the FSW yield stress is the value presented in Table 1 (300 MPa).

The roughness of the base metal is characterised by Ra (roughness average) of 0.26 µm and Rz (peak-peak) of 1.84 µm (measuring range 80 µm and cut-off 0.800 mm).

Tests were carried out at two different R ratios, 0.1 and 0.8, using for each stress ratio three different maximum loads. The R ratio of 0.1 represents pressure cycling (proof test, leak test, etc.), and the R ratio of 0.8 represents external loads during operation. Load frequencies of 8 Hz and 15 Hz were used for R ratios of 0.1 and 0.8, respectively. The tests were performed according to the matrix presented in the following Table 2.

2.2. Test procedure and setup

These tests were carried out in a MTS 810 servo-hydraulic machine with a 100kN load cell. A mechanical grip fixture was developed in order to comply with the specimen geometry and maximum loads defined in the general test plan [16]. The geometry of each specimen was accurately measured before each test, especially in the section of the material affected by the welding process.

Table 1
Strength values for test definition and performance.

	$R_{p0.2}$ (σ_{yield})
2195 T8X	510 MPa
2195 T8X FSW	300 MPa

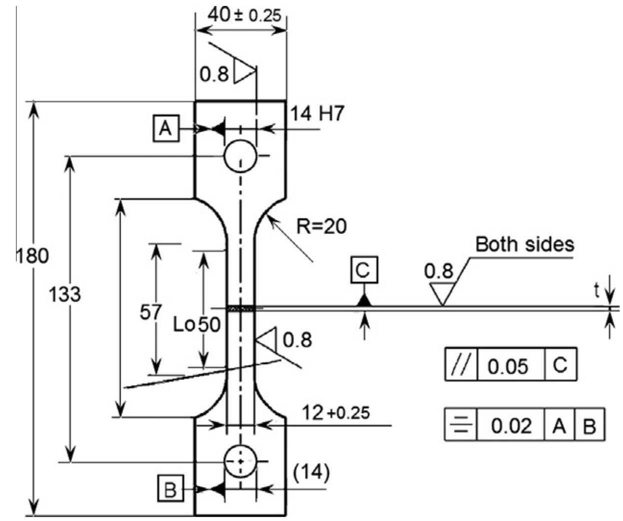

Fig. 1. Geometry of the specimen to be use in the fatigue tests (SN).

Table 2
SN tests, definition of remote loads matrix.

R ratio	Number of specimens	σ_{max}	Maximum load (kN)
0.1	2	FSW σ_{yield}	18.00
	2	85% FSW σ_{yield}	15.30
	2	70% FSW σ_{yield}	12.60
0.8	1	FSW σ_{yield}	18.00
	1	115% FSW σ_{yield}	20.70
	1	130% FSW σ_{yield}	23.40
	2	150% FSW σ_{yield}	27.00

3. Fatigue crack growth

Fatigue crack growth curves were evaluated according to ASTM [17,18] considering the use of M(T) specimens 5 mm thick. The initial notch is oriented in accordance with the material rolling direction (T-L according to ASTM [19]). The specimen geometry is presented in Fig. 2 [16]. For three different R ratios, R = 0.1, 0.5 and 0.8, 3 specimens were tested per each three different material conditions: base material, heat affected zone (HAZ), and weldment. The fatigue pre-cracking of the spark erosion notch was made in order to achieve a minimum of 0.2 mm sharp crack extension. At the end of the test K_c values and K–R curves were evaluated with a minimum remaining ligament of 15 mm.

A crack length of 25 mm was obtained before loading to fracture. According to [16], the crack length has been chosen such that maximum possible length for crack growth evaluation and a reasonable ligament (15 mm) before fracture can be achieved.

All experimental care was used aiming at symmetrical crack growth, which should result into a simultaneous verification of the $2a$ = 50 mm and $(W–2a)/2$ = 15 mm requirements. If unsymmetrical fatigue crack growth occurs, the criterion was to stop the fatigue crack propagation test as soon as the first ligament of 15 mm was reached.

The specimens have notches introduced in the centre of the weld, in the HAZ and in the base material (BM), as presented in Fig. 3 by lines 1, 2 and 3, respectively. The first type of specimens have notches in the centre of the weld (line 1), which coincides with the centre of the weld nugget. In the second type of specimens the crack is located in the HAZ (line 2). The positioning of