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Technical note

Modelling of crack coalescence in 2024-T351 Al alloy friction stir welded joints

Aidy Ali [a,*], M.W. Brown [b], C.A. Rodopoulos [c]

[a] Department of Mechanical and Manufacturing Engineering, University of Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[b] Department of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield, S1 1JD, United Kingdom
[c] Department of Mechanical Engineering and Aeronautics, University of Patras, Rion-Patras, GR26500, Greece

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ABSTRACT

In the present work, FSW of 2024-T351 Al alloy is characterised in terms of weld residual stress and cyclic properties. A fatigue endurance of the FSW joint was also investigated and discussed. Critical areas for natural fatigue crack initiation in FSW are pinpointed. The fatigue mechanism in FSW is identified to follow a multiple crack coalescence nature. The numbers of cracks participate in coalescence and the resulting crack growth rate is governed by the distance between the crack tips from crack initiation to coalescence. The above represents a complex condition for modelling. During fatigue bending tests, surface crack initiation and growth were monitored by means of a plastic replication technique. Detailed analysis revealed that under that the FSW specimen failures in fatigue bending tests are mainly a process of crack growth with initiation from defects and oxide inclusions, causing subsurface crack formation. Multiple crack initiation sites were observed from different microstructural regimes in the non-uniform residual stress distribution across the weld. This indicates that failure is dominated by fatigue crack propagation from defects. Therefore mechanisms that include features such as defect size and residual stress were considered when applying crack growth analyses to lifetime predictions. Based on crack growth and characterisation of FSW joints, a modified version of the Hobson–Brown is adopted. The good correlation achieved between the experimental data and the model predictions is presented in this paper. Satisfactory predictions of FSW lifetimes are derived from the model.

1. Introduction

Friction stir welding (FSW) is a solid state welding process that has received the worldwide attention, particularly for joining aluminium alloys [1,2]. There have been numerous attempt on characterisation in term of macrostructure, microstructure, hardness and residual stress distribution in connection with the FSW of aluminium alloys such as 2024 [3–6], 7075 [7], 7050 [8], 6061 [9], 6013 [10], 6063 [11], 1050 [12], 1100 [9,13], 1080 and 5083 [14]. There have been also tremendous investigations on fatigue issues concerning friction stir welding [3,4,6,8]. Nevertheless there is no systematic attempt to model the crack growth in FSW. Perhaps the existence of inhomogeneous of microstructure, hardness and residual stress distribution in FSW was lead to complication in the process of development of the fatigue model.

In fatigue, many attempts have been made to model the fatigue crack growth rate (FCGR) from the simplest empirical model by Paris [15] to advanced and contemporary models such as the Weertman [16] strain energy model, Tomkins [17] high strain model, Coffin [18] plastic strain model, Hobson–Brown model [19] and Navarro and de Los Rios [20–22] N–R models.

Among the many types of crack growth model stated above, the Hobson–Brown model is adopted in the present work because of its main advantage, that is simplicity, and its empirical formulation is derived directly from experimental results. Based on the simplicity of the Hobson–Brown model for short crack studies, it has been demonstrated to work very well by several researchers [23–28] as a basis when analysing their experimental results and estimating life. New advancements made by Nong Gao [28] successfully modified the Hobson–Brown model to incorporate coalescence behaviour caused by multiple crack initiation in his creep-fatigue test results. Based on crack growth and characterisation of FSW joints, a modified version of the Hobson–Brown [28] is adopted. The modified model was use to predict the fatigue life of FSW polished, FSW as welded, FSW peened as welded, FSW peened skimmed and Parent materials specimens.

2. Experimental

2.1. Material and specimens

The friction stir welded plates to produce the samples were provided by Airbus UK Ltd. Plates $75 \times 60 \times 13$ mm were welded along their long edge with the weld direction parallel to

* Corresponding author. Tel.: +60 389466437; fax: +60 386567122.
E-mail address: aidy@eng.upm.edu.my (A. Ali).

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the longitudinal (rolling) orientation. Welding parameters were kept confidential to them. The friction stir welded peened samples were produce by Metal Improvement Company. Controlled shot peening parameters were kept confidential to them. The peening operations were carried out on two conditions of sample, peened as welded and peened after skimmed off the top surface of the weld by 3 mm thickness.

Fatigue endurance tests of FSW were carried out on longitudinal specimens of length 80 mm and width of 60 mm in four point bending test in accordance with ASTM D6272 (1998). The tests configuration was similar with in work [44]. For optical observation purposes, cross section of the welds were mechanically polished to a 1/4 μm finished lightly etched in Keller's reagent in accordance with ASTM E340-00. Fig. 1a shows a transverse macrosection of a FSW joint. The most obvious feature is the well-defined nugget (N) in the centre of the weld. On top of the nugget, it is evident to identify a 'Flow Arm' region between the N and the top surface on which welding was carried out. Further out from the plate joint line (PJL) about 10 mm is the thermo-mechanically affected zone (TMAZ), see Fig. 1b. The size of this region is wide up to 4 mm, on the top welding surface and narrows down through out the thickness of 10.5 mm from the plate surface. Next to the TMAZ region is the heat affected zone (HAZ). The size of this region is narrows down to 4 mm on the top welding surface and widens through out the thickness of the plate. It is worth noting that the TMAZ region is absent on the bottom of the weld, and regions size and shape are not symmetrical in both right and left sides, due to pin rotational direction. The coordinate boundaries of each macrostructural phase were mapped by using optical PolyVarMet microscopy as shown in Fig. 1b.

2.2. Cyclic deformation behaviour test procedure

In order to investigate the cyclic deformation behaviour for each microstructural regime in FSW, fully reversed pure cyclic bending tests were performed under displacement control for strain ranges 0.1% and 2.5%. In these tests, the specimens were cut-off from each microstructural regime with different cross section size as shown on Fig. 2. The specimens were numbered according to their regime as Nugget, Composite of TMAZ and HAZ, HAZ and Parent plate with number 1, 2, 3, and 4, respectively.

2.3. Crack propagation test and measurement techniques

Crack propagation tests were performed in accordance with the standard test method for measurement of fatigue crack growth rates describe in ASTM E 647 (2000). The tests were carried out at constant amplitude, constant frequency of 20 Hz, and constant stress ratio of $R = 0.1$. The polished mirror specimens were used in order to avoid the surface irregularities of as welded specimens that could hide any small surface crack from detection.

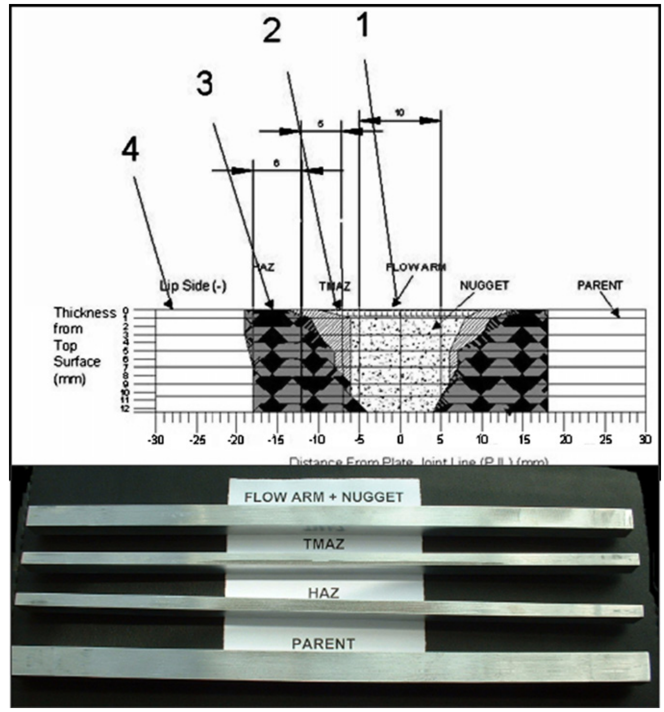

Fig. 2. Cutting scheme for the bending cyclic test.

The surface plastic replication on specimens in these tests was carried out using cellulose acetate sheet of 35 μm thickness, together with acetone spread over the specimen surface. The plastic replicas were left, during each period of replication, for about ten minutes to dry out completely. After that, they were peeled off from the specimen surface, and mounted flat on a microscope glass slide for subsequent microscopic examination. The replicas were placed approximately every 5000 cycles.

In the tests large acetate strips with an area of 60 mm × 20 mm were applied at the middle of specimen, where the highest bending stress occur, when the specimen was held under maximum stress. In this condition, the cracks on the surface were fully open. Nevertheless, the same process was duplicating every time, in case of bubble formation under the acetate sheet, which could deteriorate crack information on the replicas.

The cracks on the replicas were measured from one tip to the other, in a straight line. Their length is defined as surface crack length, a_s. The surface cracks data from replica measurement were used to calculate the crack growth rate and life. Crack growth rate was calculated using Secant, BS DD 186 (1991), ASTM E647 of 3 and 5 point (incremental polynomial) methods.

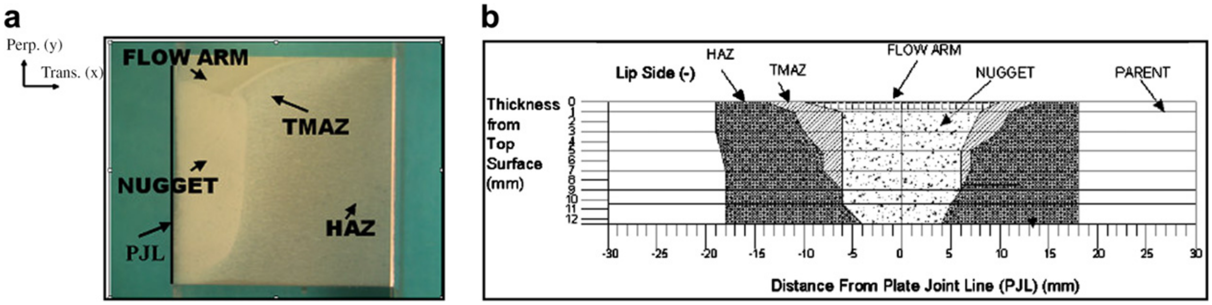

Fig. 1. The transverse cross section in an as welded FSW 2024-T351 Al Alloy joint and the mapping of boundaries between each macro structural zone.