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2198 Al–Li plates joined by Friction Stir Welding: Mechanical and microstructural behavior

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ABSTRACT

Al–Li alloys are characterized by strong anisotropy. 2198 Al–Li sheets were joined via Friction Stir Welding (FSW) in parallel and orthogonal direction with respect to the rolling one. The material microstructure and the different phases were individuated by means of TEM observations in different sections of the produced joints; in addition, the mechanical properties were evaluated by means of tensile and fatigue tests at room temperature; the fatigue tests were conducted in axial control mode with $R = \sigma_{\min}/\sigma_{\max} = 0.33$ for different welding conditions. The crack initiation and propagation in the welded zone was also studied by applying thermoelastic stress analysis (TSA) during cyclic fatigue tests, employing single edge notched specimens. Thermoelastic data were used to measure the principal stresses and principal strains on the specimens surface around the crack tip, according to growth rate; all the results were validated by employing finite element analysis (FEM) to model the crack evolution.

1. Introduction

Friction Stir Welding technology, if compared to traditional welding techniques, reduces the presence of distortions and residual stresses [1–4] and is being targeted by modern aerospace industry for high performance structural applications. Based on friction heating at the facing surfaces of two sheets to be joined, in the FSW process a special tool with a properly designed rotating probe along the contacting metal plates, produces a highly plastically deformed zone by the stirring action. The microstructure evolution and the resulting mechanical properties depend strongly on the variation of the processing parameters, leading to a wide range of possible performances [7]. The thermo-mechanical affected zone is produced by friction between the tool shoulder and the plate top surface, as well as plastic deformation of the material in contact with the tool [5,6]. The FSW process is a solid state process, therefore the problem related to the presence of brittle inter-dendritic and eutectic phases due to solidification structures is eliminated [7]. The low mechanical properties microstructure resulting from melting and re-solidification are absent in FSW welds, leading to improved mechanical properties such as ductility and strength alloys with low residual stresses [8–12]. The application of FSW technology is in particular dependence on mechanical performances affected by the processing parameters, since fatigue is the principal cause of failure for welded joints; as James et al. [13] showed the different fatigue behavior of two Al–Mg alloys as a function of welding speed. In addition, Ericsson and Sandtrom [14] and Dickerson and Przydatek [15] showed the variation of fatigue life of AA6082 joints with the welding speed and Al–Mg and Al–Mg–Si alloys plates of different thickness, comparing the results with conventional fusion welding techniques. Recent papers were published regarding the microstructural and mechanical properties of friction stir welded Al–Li alloys; in particular Hao et al. presented interesting results of tensile and bending mechanical properties as a function of processing parameters in 1420 alloys [16]. In the present work, 2198 Al–Li sheets were joined via Friction Stir Welding (FSW) in parallel and orthogonal direction. The mechanical properties were evaluated by means of tensile and fatigue tests at room temperature for different welding conditions; in addition the material microstructure and the different phases were individuated by means of optical and TEM observations in different sections of the produced joints. The crack propagation in edge-cracked specimens beside the welded zone was also studied by applying thermoelastic stress analysis (TSA).

2. Experimental procedure

2.1. Materials and methods

The material under investigation was a 2198-T851 aluminium–lithium alloy produced by ALCAN (Toronto, Canada) under the

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Table 1
Tool geometry.

Tool parts	Dimensions (mm)
Pin length	4.64
Pin diameter	5.67
Shoulder diameter	9.5

form of rolled sheets of 5 mm thickness with the following composition (wt%): Si 0.03, Fe 0.04, Cu 3.3, Mn 0.01, Mg 0.32, Cr 0.01, Ni 0.01, Zn 0.02, Ti 0.03, Zr 0.11, Pb 0.01, Li 1.0, Al bal. Rectangular plates 200 mm length × 80 mm width were welded in perpendicular and parallel direction with respect to the rolling one. The employed rotating velocities (in clockwise direction) of the cylindrical threaded tool was 1000 rpm, while the advancing selected speed was 80 mm/min with tilt angle set equal to 2°. The flat tool geometry dimensions are reported in Table 1. Some sheets were instrumented with thermocouples embedded in the parent material at different position, in order to monitor the temperature profiles as a function of the distance from the weld line; K-type thermocouples with a sheath diameter of 1 mm were employed; different thermocouples configurations were used in order to map the different thermal history of the material as shown in Fig. 1. Tensile tests were performed in order to evaluate the mechanical properties obtained in the different welding conditions. The Residual Stresses were also calculated in longitudinal direction respect to the loading one, by employing the $\sin^2\Psi$ method [17]. The RS were measured in longitudinal direction, being the one affecting the crack tip stress field. The tensile tests were carried out at room temperature using a MTS 810 testing machine with initial strain rate of $10^{-3}\ \text{s}^{-1}$. Specimens were sectioned in the perpendicular direction to the weld line by employing an electrical discharge machine (EDM), the tensile specimens measured 12 mm width, 80 mm length for a gauge length of 25 mm. Endurance fatigue tests were performed by a resonant electromechanical testing machine under constant loading control up to 80 Hz, with sine wave loading (TESTRONIC™ 25 ± 25 kN, produced by RUMUL, SUI) in high cycles regimes. The cyclic fatigue tests were conducted under axial stress amplitude control mode with loading ratio $R = \sigma_{\min}/\sigma_{\max} = 0.33$. The fatigue specimens gauge dimensions measured 12.5-mm width, 50-mm length and tests were performed up to failure. Specimens for the microstructural analyses were prepared by standard metallographic techniques and etched with Keller's reagent to reveal the grain structure. The microstructure and the different phases were individuated by means of TEM observations in the center of the joints and at distances of 2.5, 5. 7.5 and 10 mm from the weld center. For TEM investigations, thin foils were prepared by means of double jet electro-polishing, using a solution of 20% HNO3 in methanol (18 V and −35 °C). The fatigue crack propagation experiments were performed by employing single edge (1 mm) notched specimens obtained on the advancing side. The FSW, in fact, does not produce a symmetric deformation respect to the center line of the advancing tool [18]. Due to such inhomogeneities, when a clock wise direction rotation is employed, the less resistant zone results the one on the advancing side of the tool. From previous studies performed by the authors, it was demonstrated for 6082 aluminium alloy the fractured zone for tensile and fatigue specimens resulted the one on the advancing side of the tool. In such experiments a clock wise direction rotation was employed in a wide range of processing speeds [19]. The use of TSA has been optimized at tracking the crack initiation and growth.

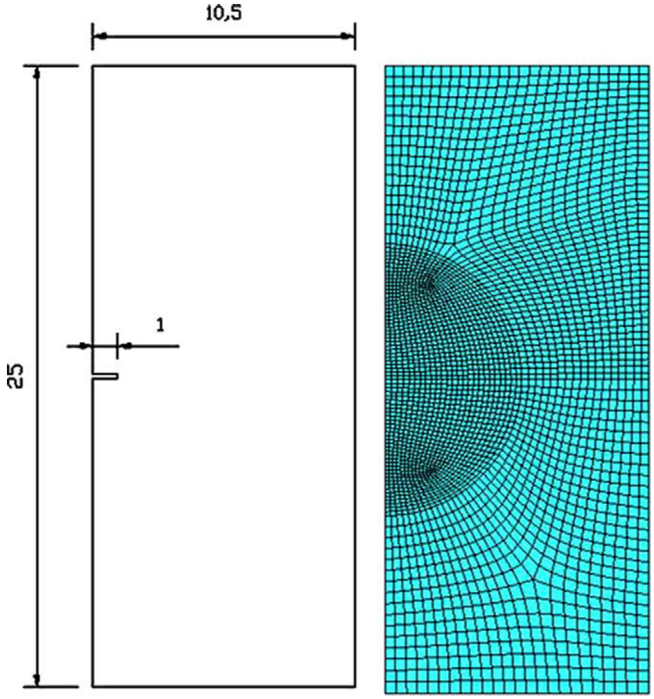

Fig. 1. Thermocouples measurements points used for the temperatures profiles during the joining process.

2.2. Principles of TSA

Not many papers exist on the evaluation of fatigue behavior of materials using instead thermographic infrared techniques [20–24]. These techniques are contactless and able to investigate areas rather than just single surface points; analysis of the stress fields around a crack tip is performed starting from 2D images which show the temperature distribution over the sample surface. The more recently developed DeltaTherm system makes possible to actually perform real-time investigation of the crack propagation, based on a much faster data collection [25–28]. The use of TSA is therefore aimed at tracking the crack initiation and growth in relation to the different areas in which it could take place; areas which are affected in various ways by the weld presence. In particular, the stress intensity factor was numerically evaluated taking into account a term including the residual stresses effect (which was calculated apart using a weight function) and subsequently compared to that inferred from TSA [29–31].

Many papers describing the principles of TSA methods and instruments are reported in literature [29–36].

2.3. K_I numerical evaluation for crack analyses

The evaluation of effective *J*-integral is largely recognized as an important method for the analysis of materials response in fracture mechanics problems. It is related to the energy release associated with the crack growth and gives the measure of the deformation at the crack tip. In the case of linear materials it can be related to the stress intensity factor. In the quasi-statically loaded stationary cracks the *J*-integral can be defined as:

$$J = \lim_{\Gamma\to 0}\int_{\Gamma} n\cdot H\cdot q\,d\Gamma, \tag{1}$$

where Γ is a contour starting on the bottom surface of the crack and ending at the top surface in anti clockwise direction. The limit $\Gamma \to 0$ indicates that Γ dimension decreases at the crack tip, q is a vector in the direction of the crack growth and n is the vector perpendicular to the Γ contour. The factor H is described by:

$$H = WI - \sigma\frac{\partial u}{\partial x}, \tag{2}$$