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Laser Shock Processing influence on local properties and overall tensile behavior of friction stir welded joints

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ABSTRACT

Based on laser beam intensities above 10^9 W/cm^2 with pulse energy of several Joules and duration of nanoseconds, Laser Shock Processing (LSP) is capable of inducing a surface compressive residual stress field. The paper presents experimental results showing the ability of LSP to improve the mechanical strength and cracking resistance of AA2024-T351 friction stir welded (FSW) joints. After introducing the FSW and LSP procedures, the results of microstructural analysis and micro-hardness are discussed. Video Image Correlation was used to measure the displacement and strain fields produced during tensile testing of flat specimens; the local and overall tensile behavior of native FSW joints vs. LSP treated were analyzed. Further, results of slow strain rate tensile testing of the FSW joints, native and LSP treated, performed in 3.5% NaCl solution are presented. The ability of LSP to improve the structural behavior of the FSW joints is underscored.

1. Introduction

Starting early 1920s, aerospatial structures have used aluminium alloys due to their high strength-to-weight ratio developed through precipitation hardening. However, the presence of precipitates within these alloys leads to poor corrosion resistance [1–3]. Therefore the structural use of aluminium alloys requires the development of treatments to improve their corrosion resistance.

It was proved that traditional fusion welding techniques are not able to provide qualitative joints made of high strength aluminium alloys because of the high power concentration needed; moreover, these alloys exhibit the tendency for both solidification and liquation cracking [2,4].

Since in the early '90s the new technique of Friction Stir Welding (FSW) emerged, it was clear that it is very suitable for joining of aluminium alloys [1–6]. FSW brings the metal into a plastic state at a temperature below its melting point, and forms the welded joint between the two parts, stirred together under pressure [7].

Nevertheless, FSW has its limitations. It was almost generally reported that the FSW aluminium joints exhibit a slight undermatch in strength with respect to the base metal [8–9]. Moreover, the residual stress field developed during the welding process is a critical feature for the service performance of the welded joint, since it can favour stress corrosion cracking (SCC) in the presence of specific environments [3,8].

Previous investigations have shown that the maximum residual stresses are less than those induced by the traditional welding processes [10]. Across the weld region the residual stress distribution reveals an "M"-like shape, asymmetric with respect to the weld centerline, with the largest longitudinal stress components oriented along the weld line, taking values ranging from 15% to 30% of the parent material yield stress [10–12].

In the last decade it has been reported [4,8,13–15] that peening techniques like Laser Shock Processing (LSP) are local surface treatments capable of inducing deep-enough compressive residual stress to moderate or even to neutralize the welding residual tensile stress field.

LSP consists of the application of a high intensity pulsed Laser beam (irradiance, $I > 10^9$ W/cm^2, and pulse duration, $\tau < 50$ ns) on a metallic target forcing a sudden surface vaporization that immediately produces a high temperature and density plasma capable of inducing a mechanical shock wave which propagates into the material [10–11].

The main objective of the investigation was to assess the ability of LSP in modifying the overall and local mechanical behavior of the AA 2024-T351FSW joints. In this view, a video-image based system was used for displacement and strain field measurement during the tensile testing of the FSW joints, native and LSP treated. The plastic strain concentration revealed by this full-field experimental data is

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explaining the joint failure in the retreating side (RS) of the thermo-mechanically affected zone (TMAZ).

Another subsequent outcome of the investigation was to determine the local tensile behavior of the joint different zones, native or superficially treated by LSP. Finally, the LSP effect on stress corrosion cracking (SCC) of the FSW joints is also discussed on the basis of slow strain rate tensile tests carried out in an aggressive medium.

2. Experimental approach

The AA2024-T351 aluminium alloy is an Al–Cu–Mg alloy which has been solution heat-treated, control stretched and naturally aged. It was selected due to high strength and suitable fracture toughness; its chemical composition is given in Table 1[16]. The investigation was made on 4 mm thick plates, in as received T351 conditions, without any additional surface treatment to increase the corrosion resistance.

The FSW samples were made at DEM-Instituto Superior Tecnico, TULISBON, Lisbon, using specialized equipment. The welding direction was perpendicular to the rolling direction of the AA2024 plates; the dimensions of the samples after welding were 200 mm × 250 mm. The main processing parameters for performing the FSW butt welds are presented in Table 2.

No cracks or indications of other surface-open flaws have been revealed after the visual inspection of the samples.

Tensile specimens (conventional dog bone coupons of loading direction normal to the weld), with a gauge length of 50 mm and a gauge width of 12.5 mm were machined, in accordance with ASTM E8, from the FSW joint panels and native base metal plates. The Laser Shock Processing was applied on both faces of the specimens, on a total length of 57 mm (Fig. 1). Untreated FSW specimens and base metal specimens were also tensile tested for comparison.

According to ISO 7539-7 prescriptions, the same type of specimens was used for the slow strain rate tensile tests, carried out in an aggressive environment, to measure the joints susceptibility to stress corrosion cracking.

The Laser Shock Processing was performed with a Nd:YAG laser emitting at 1064 nm (fundamental) and 532 nm (1st harmonic) wave lengths, at UPM Laser Centre, Universidad Politécnica de Madrid. A Q-switch device was used to produce the nanoseconds regime. The treatment area was covered with an approximately 1 mm thick laminar layer of flowing water, and the laser beam was brought into it by means of a set of mirrors arrangement. No other absorbing coating was used [14]. A 2D motion system was used to control the specimen position against the laser beam and generate the pulse swept (Fig. 1b). The LSP surface sweeping strategy, namely the equivalent number of laser pulses per unit area of processed surface was obtained by controlling the system velocity and the pitch overlapping. The processing parameters are given in Table 3.

Tensile testing was performed at Materials Science Dpt., E.T.S.I. Caminos, Universidad Politécnica de Madrid, at room temperature on a 200 kN servo-hydraulic universal testing machine using a constant crosshead speed of 1 mm/min. A Video Image Correlation system (VIC-2D) was used additionally to conventional clip-on extensometers to assess the strain and displacement fields during tensile loading of the LSP treated and untreated FSW specimens.

VIC-2D is a displacement and strain measurement technique capable to analyze the digital images data taken during a tension test of a flat specimen. The camera is placed perpendicular to the specimen surface and its calibration requires only the determination of the scale factor. Consecutive digital images are used to monitor the changes of a speckle pattern, previously applied on the specimen surface. The system uses an iterative spatial domain cross-correlation algorithm to track the speckle pattern movement during loading. The error in the in-plane strain and displacement measurements due to out-of-plane motion of the target surface is proportional to the ratio of the out-of-plane displacement to the focal length of the camera, and is typically less than 1%.

The system was used to assess the longitudinal strain distribution over an area of interest (AOI) defined on the specimen surface, containing the FSW joint, LSP treated or not, during tensile loading. The results were used to obtain strain averages data vs. *testing time*, using "virtual extensometers", on gauge lengths comparable with the lengths of different weld regions. The average strains were mapped to the corresponding global stress levels applied by the testing machine, assuming that the transversely loaded FSW specimens were in iso-stress configuration.

Table 1
Nominal weight percentage for AA2024 chemical composition.

Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Bal	0.10	3.4–4.9	0.50	1.2–1.8	0.3–0.9	0.50	0.15	0.25

Table 2
FSW processing parameters.

FSW parameters	
Pin length, mm	4.17
Tilt angle, °	0
FSW control	Vertical force control
Vertical downward forging force, kgf	890
Rotation speed, rpm	1000
Rotation direction	CW
Travel speed, mm/min	300
Plunge speed, mm/s	0.1
Dwell time, s	8
Rolling direction vs. weld line	Perpendicular

3. Results and discussion

3.1. Welded joint microstructure

Standard procedures were used to prepare the metallographic specimens. Different etching reagents were used to obtain high

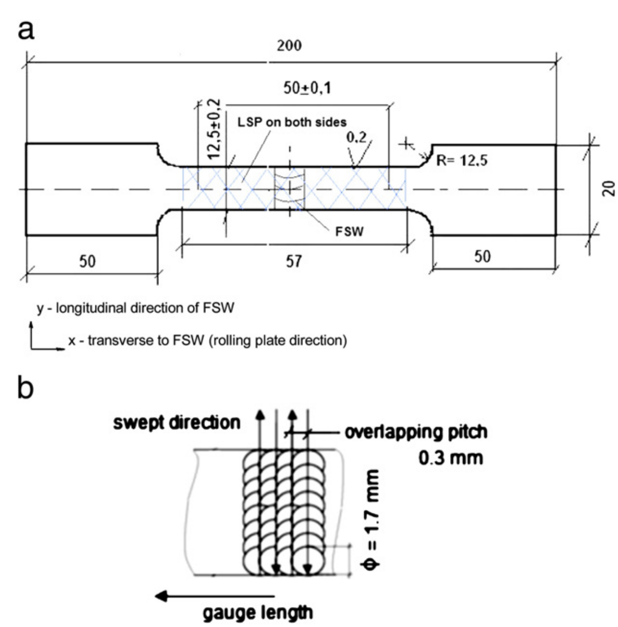

Fig. 1. Sketch of the FSW and FSW with LSP specimen used for tension and SSC testing: a) specimen geometry with dimensions in mm; b) LSP surface sweeping strategy.