Materials Science and Engineering A 492 (2008) 168–176

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Effects of peening on mechanical properties in friction stir welded 2195 aluminum alloy joints

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ARTICLE INFO

Article history:
Received 19 December 2007
Received in revised form 5 March 2008
Accepted 6 March 2008

Keywords:
Friction stir welding
Laser peening
Shot peening
Mechanical properties
2195

ABSTRACT

The effects of surface treatment techniques like laser and shot peening on the mechanical properties were investigated for friction stir welded 2195 aluminum alloy joints. The loading in the tensile specimens was applied in a direction perpendicular to the weld direction. The peening effects on the local mechanical properties through the different regions of the weld were characterized using a digital image correlation technique assuming an iso-stress condition. This assumption implies that the stress is uniform over the cross-section and is equal to the average stress. The surface strain and average stress were used giving an average stress–strain curve over the region of interest. The extension of the iso-stress assumption to calculate local stress–strain curves in surface treated regions is a novel approach and will help to understand and improve the local behavior at various regions across the weld resulting in a sound welding process. The surface and through-thickness residual stresses were also assessed using the X-ray diffraction and the contour methods. The laser peened samples displayed approximately 60% increase in the yield strength of the material. In contrast, shot peening exhibited only modest improvement to the tensile properties when compared to the unpeened FSW specimens. The result that laser peening is superior to shot peening because of the depth of penetration is original since this superiority has not been presented before regarding mechanical properties performance.

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1. Introduction

High strength aluminum alloys are used extensively in the aerospace industries due to their strength and light weight. However, these aerospace aluminum alloys are traditionally considered to be unweldable using conventional fusion welds [1] because of the dentretic structure formed with the fusion welding [2]. Dentretic structure typical of a fusion weld joint can seriously degrade the mechanical properties of the welded joint [3]. Since its invention by the Welding Institute in 1991 [4], friction stir welding (FSW) has emerged as a promising solid state process with encouraging results. This welding technique has potential significant application in different fields including the automotive and aerospace industries [5], and has resulted in welded joints being used in critical load bearing structures and structurally demanding applications [6].

The FSW technique employs a non-consumable cylindrical pin that rotates at high speeds and is then plunged into butting edges of the work pieces to be joined [2]. This process transforms the metal into a plastic state at a temperature below the melting temperature of the material [7], and then mechanically stirs the material together under pressure to form a welded joint. Since FSW is considered a solid state welding process, significant differences compared to conventional welding may be expected in terms of heat affected zone (HAZ) size and microstructure, and residual stress fields around the weld [8].

The FSW consists of a nugget, the thermo-mechanical affected zone (TMAZ), and a heat affected zone. FSW takes place at a low temperature level compared to fusion welding; therefore, residual stresses may be considerably less than those in fusion welds. Nevertheless, the rigid clamping configuration required to clamp the parts during the FSW process along with the heating cycle the material experiences during welding, can result in higher residual stresses in the weld [9,10]. These residual stresses, along with the reduction in properties from the welding process are likely to affect the mechanical properties and therefore influence the in-service performance of structural components [11]. The weld strength in some cases can be improved by post-weld heat treatment. However, this is not always an option in welded structural components. Consequently, laser shock peening was investigated as a mean for improving the tensile properties in FSW.

Laser shock peening is an efficient surface treatment technique that has been proven to be capable of improving the fatigue and mechanical properties of a number of metallic materials [12–15]. The laser peening process (Fig. 1) provides high energy laser pulses

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0921-5093/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.msea.2008.03.017

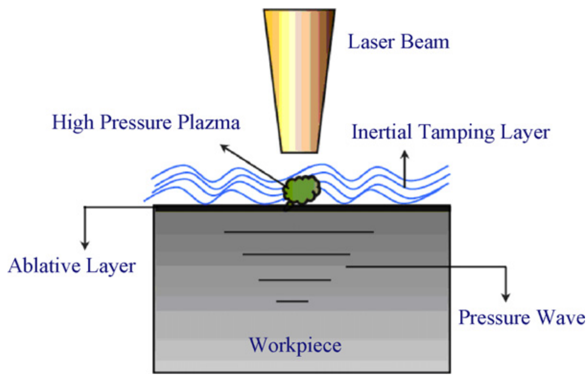

Fig. 1. Laser peening process.

that are fired at the surface of a metal coated with an ablative layer, and covered with a thin layer of transparent material (usually water). As the surface layer ablates, the water confines the evaporating material and the vapor is ionized to form plasma. The subsequent laser energy is absorbed by the plasma and generates a high intensity shock wave that impinges on the metal. When the peak pressure of the shock wave is greater than the dynamic yield strength of the material, it produces extensive plastic deformation in the metal. The laser peening process generates a compressive residual stress at the surface that can be significantly deeper than for conventional shot peening [15–17]. The actual depths of the laser-peening induced stresses will vary depending on the material properties of the peened parts and the processing conditions chosen [18].

Several investigations [5,19–20] have assessed the local tensile properties on FSW, however none have assessed the effects of laser peening on the tensile properties on FSW. Since the overall tensile stress of the weld is connected to the local mechanical properties in the weld region; understanding and improving the local behavior at various regions across the weld will result in a sound welding process. In this study, shot peening and laser peening were used to introduce compressive residual stresses into FSW AA 2195. The influence of the peening on the mechanical properties of the FSW specimens were characterized and assessed. Since conventional transverse tensile testing only provides the overall strain experienced by the sample, the local strains and equivalent tensile properties were evaluated at different regions of the weld using a digital image correlation (DIC) system.

2. Experimental setup

Aluminum alloy (AA) 2195-T8 plates with a 1.25 cm thickness were used in this research. The aluminium plates were welded together by a single pass using a rotational speed of 300 rpm in the counterclockwise direction and a translation speed of 15 cm/min. The welds were oriented parallel to the rolling direction. The mechanical properties for the base material are as shown in Table 1. Both the root and the crown sides of the weld were tested to evaluate the quality of the weld. The samples were inspected visually afterward with no crack indications revealed.

The tensile specimens were either shot-peened or laser-peened. Unpeened FSW samples were also tested and used as a baseline. To optimize the shot peening process, Peenstress, which is a software developed at the Metal Improvement Company, was used. Based on this evaluation, the samples were shot-peened with 0.059 mm glass beads, with an Almen intensity of 0.008–0.012 A and a 200% coverage rate. The impinging shots were fired at the surface of the specimens at an angle in order to avoid collision with the rebounding beads.

Table 1
Tensile properties for the as received AA 2195-T8

Material	0.2% Yield stress (MPa)	Ultimate strength (MPa)
2195-T8	503	537

For the laser peening process, different peening layers were used in this study in an effort to identify the optimum number of peening layers capable of producing superior tensile properties. Prior to the laser peening process, the surface of the specimens intended for peening was covered with a 0.22 mm thick aluminium tape, which was replaced between layers of peening. A 1 mm thick laminar layer of flowing water was used as a tamping layer. The laser peening was applied using a square laser spot with a laser power density of 5 GW/cm^2 and 18 ns in duration. The spots within a layer were overlapped 3%. All four sides of the gauge section in the specimens were peened using the same conditions.

The surface residual stresses were measured using the X-ray diffraction (XRD) technique. In XRD, the strain in the crystal lattice is measured assuming that the crystal lattice is linearly distorted. The atomic spacing (d) between crystallographic planes that are equal will vary consistently with their psi (ψ) angle, where the ψ angle is defined as the "angle between the surface normal and the normal to the crystallographic planes from which the X-ray peak is diffracted" [21]. Therefore, to determine the magnitude of residual stresses, the lattice strains are assessed in various ψ directions and a plot of $\sin^2\psi$ vs. $\varepsilon_{\o\psi}$ is derived (where $\o$ is the angle between a reference direction and the direction of stress measurement in the plane). $\varepsilon_{\o\psi}$ is the strain in the $\o$ and ψ directions defined by [22]:

$$\varepsilon_{\phi\psi} = \frac{1+\nu}{E}(\sigma_\phi \sin^2\psi) - \frac{\nu}{E}(\sigma_1+\sigma_2) \tag{1}$$

where ν: Poisson's ratio; $\sigma_\o$: surface stress at an $\o$ angle with a principal stress direction; E: modulus of elasticity; σ_1, σ_2: principal stresses.

Then from the $\sin^2\psi$ vs. $\varepsilon_{\o\psi}$ plot, residual stresses are established through the following relation:

$$\sigma_\phi = \frac{mE}{1+\nu} \tag{2}$$

where m = slope of the $\sin^2\psi$ vs. $\varepsilon_{\o\psi}$ plot.

Residual stress were acquired using a Philips X'Pert PW3040 MRD X-ray diffractometer, equipped with a pole figure goniometer, operating at 40 kV and 45 mA, and employing Ni filtered Cu K-alpha radiation. The measurements were taken using 2θ scans from 77° to 79°, with 0.01° per step and 1 s per step, (3 1 1) peak positions at 10 different tilt angles.

The through-thickness residual stresses for the FSW sample were measured using the contour method [23] on the plane outlined in Fig. 2. To perform the technique, the specimen was cut along the measurement plane with an EDM wire. In order to minimize movement during the cutting process, the specimen was fixed to a rigid backing plate. The deformed surface shape resulting from the relaxed residual stresses was measured on both cutting surfaces using a coordinate measuring machine (CMM). The displacements from both cutting surfaces were then averaged and noise in the measurements was filtered from average displacements by fitting to a smooth analytical surface. Finally, the original residual stresses were calculated from the measured contour using a finite element model (FEM).

Tensile testing was performed at room temperature on a 200 kN servo-hydraulic universal testing machine using a constant crosshead speed of 0.1 mm/min. The transverse tensile specimens