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Fatigue crack growth performance of peened friction stir welded 2195 aluminum alloy joints at elevated and cryogenic temperatures

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ABSTRACT

The effects of various surface treatments on fatigue crack growth and residual stress distributions in friction stir welded 2195 aluminum alloy joints were investigated. The objective was to understand the degree to which residual stress treatments can reduce fatigue crack growth rates, and enhance fatigue life of friction stir welded components. Specimens were fabricated from 12.5 mm thick 2195-T8 aluminum plate, with a central friction stir weld along their length. Residual stresses were measured for three specimen conditions: as-welded (AW), welded then shot peened (SP), and welded then laser peened (LP). Crack growth rate tests were performed in middle-cracked tension specimens under constant amplitude load for each of the three conditions (AW, SP, LP) and at three temperatures (room, elevated, and cryogenic). At room and elevated temperature, crack growth rates were similar in the AW and SP conditions and were significantly lower for the LP condition. At cryogenic temperature, it was difficult to discern a trend between residual stress treatment and crack growth rate data. Laser peening over the friction stir welded material resulted in the fatigue crack growth rates being comparable to those for base material.

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1. Introduction

The aluminum–lithium alloys are of great interest in modern aerospace applications [1] due to their lower density, greater elastic modulus, and higher specific strengths [2] compared to traditional aluminum alloys. Aluminum–lithium alloys have been developed primarily to reduce the weight of aircraft and aerospace structures. Aluminum alloys are generally difficult to fusion weld because mechanical properties can be seriously degraded as a result of heat-induced changes to their precipitate structure and dentritic structures formed during the fusion welding process [3]. Aluminum–lithium alloys do not offer improved weldability over other high strength aluminum alloys.

Friction stir welding (FSW) [4] has emerged as a successful alternative to fusion welding for joining aluminium alloys. During FSW, welded components exhibit temperatures below their melting temperature, and the residual stresses generated during welding are generally lower than those in fusion welds. Nonetheless, the heating cycle and rigid clamping arrangement during FSW can generate elevated residual stresses in the weld [5–7]. For example, a recent investigation by Hatamleh et al. [8] on friction stir welded AA 2195 identified residual stress values around 231 MPa near the weld region. Tensile residual stresses typically degrade the fatigue properties [9] of joints and the structural integrity of weldments. For that reason, compressive residual stress treatments, through techniques like shot or laser peening, can enhance the mechanical properties of welded components [10,11], and could extended fatigue life [12–14].

Shot peening (SP) is an established surface treatment where the surface of a part is deformed plastically by multiple overlapping impacts of glass or metal spheres. Shot peening creates a shallow layer, typically 0.25–0.5 mm deep, of compressive residual stress [15,16] that can improve fatigue performance. Laser peening (LP) is a surface treatment capable of introducing a far deeper layer of compressive residual stress than SP, typically 1–3 mm deep [17], and can therefore provide a greater benefit on fatigue performance than provided by SP. LP has proven capable of enhancing the fatigue properties of a number of metallic materials [18–26].

The present paper is intended to complement recent work on FSW joints. A significant amount of recent work [27–34] has investigated the fatigue behavior of FSW aluminum alloys at room temperature in the absence of residual stress treatments. This study evaluates fatigue crack growth rate (FCGR) behavior of FSW joints in AA 2195, and compares FCGR in as-welded (AW) specimens with those treated by SP and LP. Because fatigue FCGR data are affected by residual stresses, we also measure residual stresses in the AW,

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

Material	0.2% yield stress (MPa)	Ultimate strength (MPa)	Young's modulus (GPa)
2195-T8	503	537	76

SP, and LP conditions, and then analyze the residual stress data to understand its effects on the total (applied + residual) stress intensity factor ratio active in the FCGR tests. We further evaluate FCGR behavior at a range of temperatures (room, elevated, and cryogenic), since FSW joints of aerospace structures may be exposed to a wide range of temperature in service.

2. Experimental setup

The welds for this investigation were prepared by friction stir welding several 12.5 mm thick 2195-T8 aluminum alloy (AA) plates. The mechanical properties for the base material are outlined in Table 1. Each of the welded joints consisted of two Plates 900 mm long, 150 mm wide, and 12.5 mm thick; the 900 mm length was along the rolling (L) direction of the parent plate. After welding, the joints were 300 mm wide. The plates were joined together along the longitudinal direction using a single FSW pass with a rotational speed of 300 RPM in the counterclockwise direction and a translation speed of 150 mm/min. The tool used to weld the plates had a 33 mm diameter shoulder with a 4 mm/rev scroll pattern. The pin in the tool had a tip diameter of 9.14 mm that was tapered 8°, and had a 1.5 mm/thread pitch. The spindle forward angle used for the welding process was 1°.

The welded specimens tested in this investigation were either left as-welded (AW), shot peened (SP), or laser peened (LP) over the friction stir weld. The shot peening process, selected by computer optimization, used 0.59 mm glass beads, with an Almen intensity of 0.008–0.012 A and 200% coverage. The laser peening process was applied over the desired treatment area in a raster fashion. To ensure even coverage over the whole area, the laser spots within a layer were overlapped 3%. Before the peening process, all the specimen surfaces were covered with a thin aluminum tape that was replaced in between layers of peening. A 1 mm thick laminar layer of water was used as the tamping layer. The laser peening was applied using a square laser spot with a laser irradiance of 5 GW/cm^2 and a pulse length of 18 ns. Both sides of the specimens were laser shocked using three layers of peening. The three layers

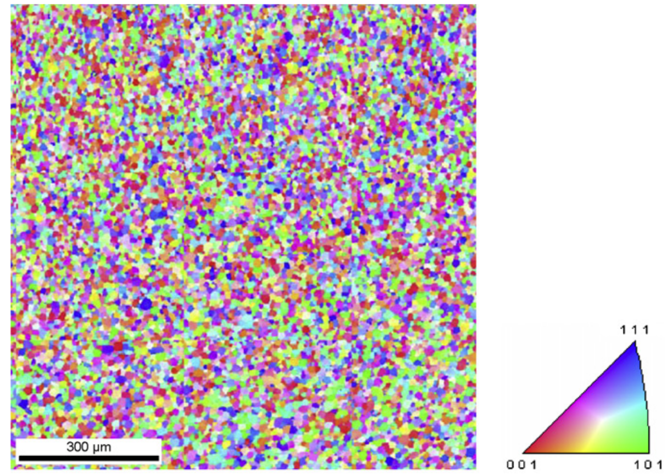

Fig. 2. Orientation map and grain size distribution for the weld nugget region in FSW 2195.

of peening correspond to the same region on the specimen being treated three different times.

The microstructure of the weld zone was assessed using optical and scanning electron microscopes. The texture of the weld was also analyzed using electron back scatter diffraction (EBSD). To prepare the specimens for the metallographic examination, the specimens were subjected to several successive steps of grinding and polishing prior to etching. To further identify the microstructural changes in the FSW regions, a microhardness profile was measured across the top of the weld surface as a function of position across the weld using a load of 300 g and a dwell of 3 s.

In order to quantify the post-FSW condition and better understand the observed FCGR behavior, surface residual stresses were measured with the X-ray diffraction (XRD) technique. In XRD, the strain in the crystal lattice is measured assuming that the crystal lattice is linearly distorted by residual stress. Measurements were collected at a Bragg angle of 162° corresponding to diffraction at the 511/333 planes. Residual stresses were measured at seven locations across the weld as shown in Fig. 1 (weld centerline, thermal-mechanical affected, heat affected zones, and base material). The contour method [35,36] is used to measure the distribution of the weld-direction residual stress component on a plane across the weld (Fig. 1). Residual stress measurements from both

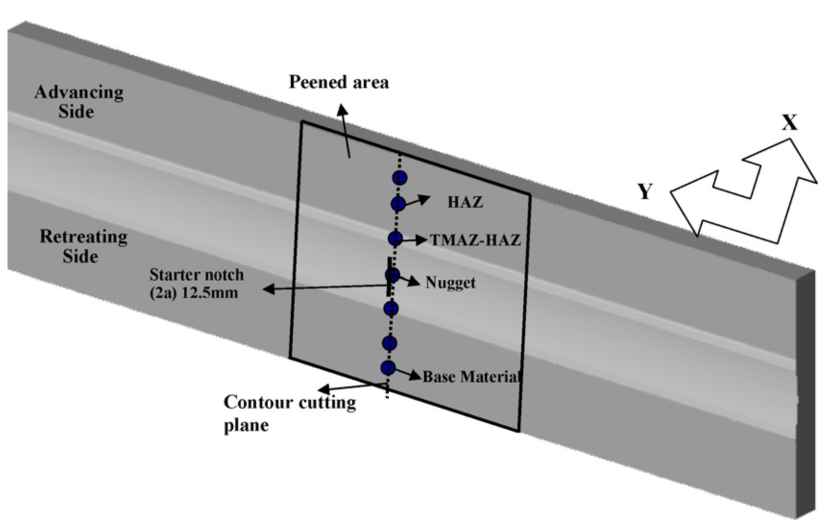

Fig. 1. Locations of residual stress measurements.