Fatigue life of friction stir welded-aluminum alloy-7010 joints

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Abstract

FSW is a solid state welding process which is widely used with high strength Aluminum Alloys (AA) such as AA-7xxx series. This alloy series is typically used in various structural applications such as truck wheels and bodies, heavy duty structures and aerospace. Durability of these structures is perhaps the most significant attribute they can possess manifesting the importance of fatigue life assessment. In this work, FSW was applied on AA-7010 using tool rotational speed of 850 rpm at a welding speed of 56 mm/min. The tool axial load was maintained constant within the whole welding runs. The resulting weldments were divided into two groups namely; as-welded and shot-peened conditions. Tensile and axial fatigue testing with stress-ratio (R=0.1) were used to evaluate and compare tensile properties and S-N curves of the welded and welded + peened conditions. The weldments were also characterized using optical microscopy, fractography, mechanical and fatigue testing as well as micro-hardness profiles across the weldment.
Keywords: friction stir welding, aluminum alloy, fatigue, fractography.

1 Introduction

Friction stir welding (FSW) is a recent method of joining materials, patented by the welding institute (TWI) in 1991. This technology is being widely considered by the modern aerospace and automotive industry for high-performance structural demanding applications [1]. In the FSW process no melting of the base metals occurs and the weld forms through solid-state plastic flow at high temperature. FSW assures the absence of porosity and thermal distortion which are typical defects of the fusion welding processes. The process uses a rotating

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tool with a pin which may have different profiles and a shoulder. The pin penetrates the parts to be joined, which, are firmly clamped, till the desired pressure is reached. The tool starts to rotate whereas the parts to be joined start moving linearly along the joint line past the tool [2]. The process set-up is shown schematically in Figure 1 [3]. The resulting heat, produced due to the friction occurring between the pin and the joint's faying surfaces and also the friction between the shoulder and the upper surface of the parts, softens the material, and the pin stirs the parts of the joint, causing them to be joined. The FS Welded material produces three different areas: the weld nugget, the thermo-mechanically affected zone and the external heat affected zone. The microstructural grain structure in the weld nugget is usually very fine and equiaxed, ensuring elevated mechanical strength and ductility [4, 5].

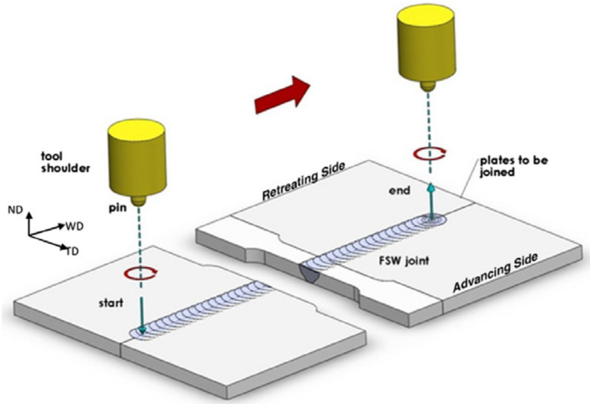


Figure 1: Schematic illustration of friction stir welding process [3].

Light-weight aluminum alloys, which are difficult to weld such as 2000 and 7000 series, have been successfully welded by FSW. These alloys are widely used to obtain components for aerospace applications with high specific strength [6, 7]. For the aircraft components fatigue performance was known to be one of the crucial assessment qualities, therefore many efforts have been done to investigate the fatigue properties of friction stir welded various grades of aluminum alloy joints [8]. As it is already known that fatigue loading is the main cause of failure of welded joints. It has been reported [9] that fatigue strength of friction stir weld joints is superior than fusion welded joints and is equal or less than base metal. The higher fatigue strength of FSW joints is because of fine recrystallized microstructure, smaller HAZ and greatly reduced residual stresses because of rigid fixing of the plates. It was noted from literature that in recent years, several investigations were carried out to evaluate the effect of FSW-aluminum alloy 7xxx series on the fatigue crack propagation behavior as well as to investigate the effect of residual stresses on near-threshold crack growth in friction stir welds. In order to reduce the negative influence of residual stresses on the weldment strength, several studies have proposed shot or laser peening to enhance the fatigue life. The aim of the present work is to investigate the influence of shot peening on the fatigue life of weldments joined by FSW and to compare it with the fatigue life in the as-welded condition.

2 Experimental works

Aluminum-7010 sheets of 250 mm length x 100 mm wide x 5 mm thick having a square edge facing each other were joined by friction stir welding. The chemical composition in wt. % 5.7 Zn, 2.4 Mg, 1.84 Cu, 0.29 Si, 0.15 Fe, 0.05 S, 0.03 Mn and the balance is aluminum. The longitudinal direction of the welding line was perpendicular to the rolling direction. The welding speed was 56 mm/min and the tool rotational speed selected was 850 rpm. The tool axial load was maintained constant within the whole welding runs. The welding tool was fixed to the rotating spindle of a vertical milling machine. The tool had a cylindrical-shouldered shape made of H13 tool steel, with a 4.7 mm long-cylindrical tool pin and 15 mm diameter shoulder. The two base metal plates were clamped firmly to the machine table. Welding begins as the tool rotates in the clockwise direction and the plates traverse longitudinally towards the rotating tool pin at a feed rate which is referred to hereafter as the welding speed. After welding the specimens were cut into strips perpendicular to the weld bead for hardness, tensile, fatigue and metallographic testing. Vickers micro-hardness measurements, 0.5 mm apart, were taken covering the entire weldment's cross section using a Vickers indenter with 200 gf load for 15 seconds. Tensile and fatigue specimens were machined according to ASTM-E8 code with a gauge length of 25 mm leaving the weld nugget exactly at the middle. Tensile tests were performed in order to evaluate the static properties of the welded joints and also the as-received base metal. Tensile tests have been conducted at room temperature using an INSTRON testing machine at a cross-head speed was set to 2mm/ min. The standard procedures of metallographic preparation in preparing the welded joints including grinding by silicon carbide papers up to grit number 1000, polished using 0.3 μm alumina suspensions, then etched by a chemical Keller etchant composed of 2ml hydrofluoric acid, 3 ml hydrochloric acid, 5 ml nitric acid and 190 ml distilled water. Fatigue testing was conducted under uniaxial tensile loading condition (Tension−Tension, R=stress ratio, $\sigma_{min}/\sigma_{max}$=0.1, Frequency=15 Hz) at four different stress levels (110, 140, 160, 170 and 185 MPa) using servo hydraulic fatigue testing machine [INSTRON, Model: 8801] under constant stress amplitude. Fatigue tests were continued up to failure or complete separation of the test specimen. Fracture surface of failed fatigue specimens were investigated by scanning electron microscope (SEM). The fatigue specimen's surfaces were fine ground using metallographic procedures using different sand paper till 2500.

3 Results and discussion

3.1 Microstructure

Figure 2 shows the base metal microstructure, which has elongated grains with an aspect ratio of 6.5. Figure 3 shows a typical macrograph of the weld zone which is usually found with FSW joints. This includes weld nugget (stir zone), thermo-mechanically affected zone (TMAZ) and the unaffected base metal (B.M.). The TMAZ which is found in the close vicinity to the weld nugget is subjected to lesser strains and also less peak temperatures. This zone is characterized as a deformed region in which the grains are distorted due to the stirring effect of the FSW tool, thus suggesting shear flow of the material about the rotating tool as found by McNelly *et al.* [10]. The grain distortion may result

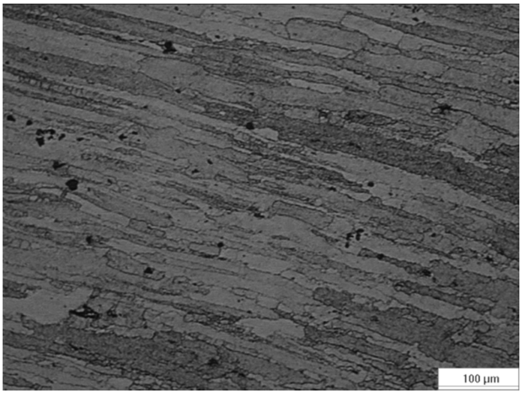


Figure 2: Base metal microstructure.

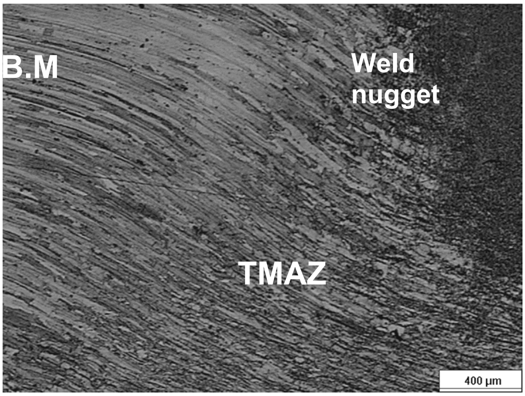
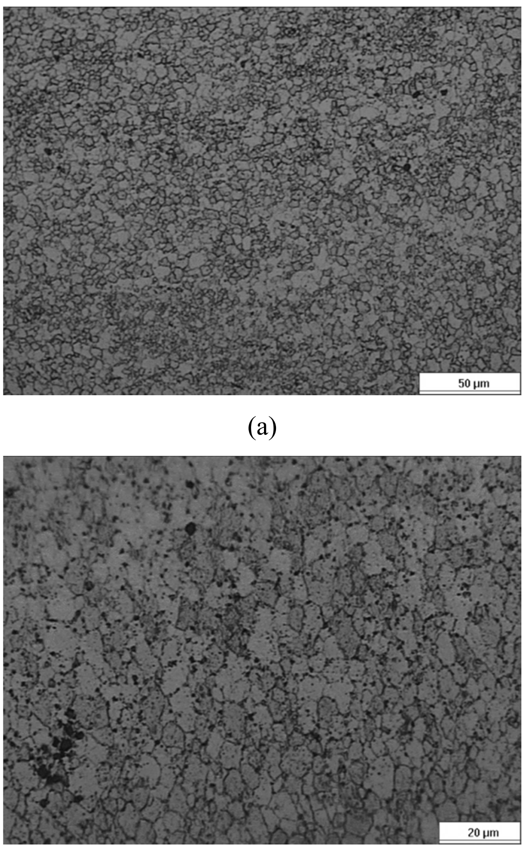


Figure 3: Weld zone macrostructure showing the transition zone. TMAZ: thermo-mechanically affected zone, B.M.: base metal.

into breaking the elongated grains leading to the formation of equiaxed grains at this zone which can be considered as partially recrystallized grains as seen in Figure 3.

The weld nugget microstructure is shown in Figure 4 and can be described as equiaxed and fine-grained microstructure. The average grain size measured by linear intercept method was about ~7 μm. This refinement resulted from the dynamic recrystallization occurring due the FSW tool stirring action, which is a simultaneous combined motion between tool rotation and work piece translation. At higher magnification as in Figure 4(b), the presence of large amounts of inclusions, intermetallics and insoluble particles which are dispersed within the entire microstructure can be noted.



(a)

(b)

Figure 4: Weld nugget microstructure at (a) low magnification and (b) higher magnification.

3.2 Hardness

The micro hardness distribution across the weldment is shown in Figure 5. It can be seen that the weld nugget is relatively harder than the TMAZ as well as the base metal reaching a maximum value of 150 HV. This is due to the fine-grained microstructure which is only present in weld nugget. The TMAZ is slightly softer than the weld nugget due to partial recrystallization. Simultaneously, the TMAZ is harder than the BM due to the strain hardening effect which has risen due to plastic deformation resulting from the stirring action.

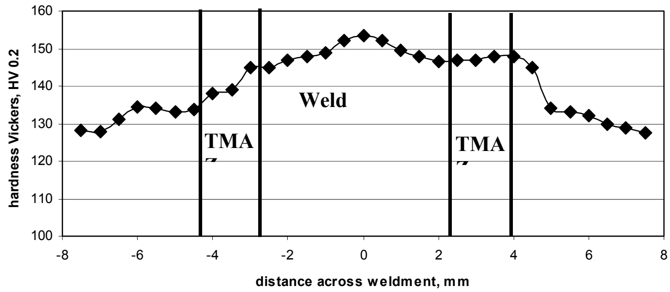


Figure 5: Microhardness distribution across the weldment.

3.3 Mechanical properties

Table 1 presents the transverse tensile properties such as yield and ultimate strengths as well as elongation expressed in strain at fracture of the base metal and the weldment. The yield strength and tensile strength of the base metal are 630 MPa and 910 MPa respectively. But the yield strength and tensile strength of FSW joint were 410 MPa and 570 MPa, respectively. This may be due to the presence of large amounts of intermetallics and precipitates which occurred due to the welding friction heat.

Table 1: Tensile properties of the base metal and FS welded joint.

	Yield strength	Ultimate tensile	True strain at fracture
Base metal	630	910	0.22
Welded Joint	420	670	0.19

Fatigue endurance tests were carried out at a frequency of 15 Hz following a sinusoidal waveform and with a stress ratio of 0.1. The S-N curves of as-welded and as-welded with shot peening is shown in Figure 6. Shot peening has slightly increased the fatigue life because it produces a superficial compressive residual stress at the surface. The compressive residual stress has been reported to be as high as 60% of the material's ultimate strength [11]. This compressive stress

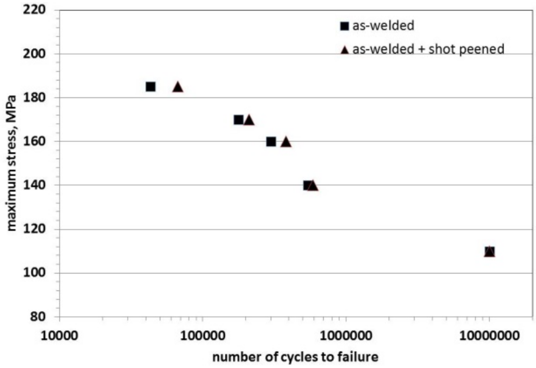
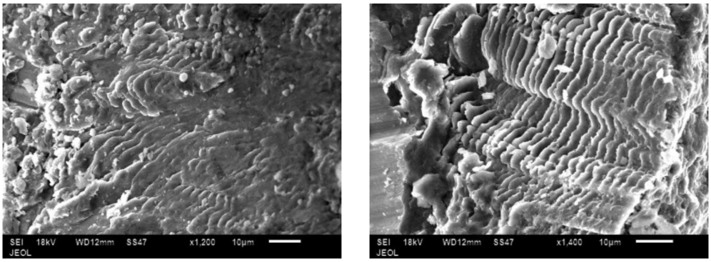


Figure 6: S-N curves of FSW joints in the as-welded and as-welded with shot peened conditions.

induces crack closure and the strain hardening reduces the amount of crack tip plasticity which acts to improve fatigue life by retarding growth of small cracks.

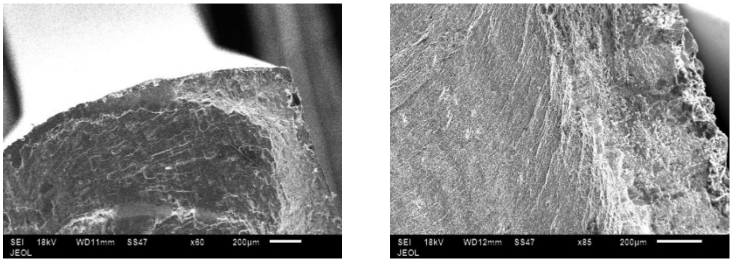
This can be further seen in Figure 7 which shows the difference in the striation spacing occurring with the two conditions. It is reported in earlier work [12] that the reduction in striation spacing indicates a slower fatigue crack growth rate which is partially attributed to the compressive residual stresses induced by shot peening.



(a) (b)

Figure 7: Fatigue fracture morphology showing striations in the conditions: (a) as-welded and (b) as-welded and peened.

Figure 8 shows that the crack initiation points in both conditions were originating from a single point at the sample's surface within the weld nugget zone. This result is in agreement with that reported in [13] which indicated that the weld nugget is the zone which is likely to introduce local stress concentrations as well as higher possibility of crack formation within the nugget area and hence the probability for premature crack coalescence due to the particles and intermetallics de-cohesion.



(a) (b)

Figure 8: Fatigue fracture morphology showing the crack initiation points: (a) as-welded and (b) as-welded and peened.

4 Conclusions

Fatigue life of friction stir welded Aluminum Alloy 7010 alloy joint in the as-welded condition is slightly shorter than the same joint after being shot peened. However, FSW produces fine-grained recrystallized microstructure at the weld nugget zone. The yield and ultimate strength were lower than that of the base metal in spite of the fact that the weld nugget was harder that the base metal. This may be due to the dissolution of precipitates during friction stir welding which needs further investigation.

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