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EFFECT OF POST WELD HEAT TREATMENT ON FRACTURE TOUGHNESS PROPERTIES OF FRICTION STIR WELDED AA7075-T651 ALUMINIUM ALLOY JOINTS

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ABSTRACT

This paper reports on investigation of the effect of post weld heat treatment on fracture toughness properties of friction stir welded AA7075-T651 aluminium alloy joints. The aim of the present work is to evaluate the effect of post weld heat treatment on fracture toughness properties of 12 mm thick AA 7075 -T651 aluminium alloy plates joined by friction stir welding (FSW) process. Compact tension (CT) specimens were prepared to evaluate the plane strain fracture toughness of the welded joints. The fracture toughness properties were evaluated under uniaxial tensile loading condition (stress ratio = 0.1, Frequency =10Hz) at room temperature using servo-hydraulic controlled machine. The resultant fracture toughness properties were correlated with the tensile, hardness and microstructural characteristics of welded joints. The mode of failure was analyzed through scanning electron microscopy. From this investigation, it is found that the fracture toughness values of friction stir welded AA7075 aluminium alloys are lower than that of the fracture toughness values of friction stir welded post weld heat treatment (solution treated followed by aging (STA)) joints.

Keywords: *AA 7075 aluminium alloy; Friction stir welding; Fracture toughness; post weld heat treatment*

1. Introduction

The 7XXX series (Al–Zn–Mg–Cu) aluminium alloy thick plates have been extensivelyused in aerospace industry to produce the components of airplane such as skeleton parts, bulkhead, longer on and so forth [1]. Zinc and magnesium are the main alloying elements. The undesirable iron and silicon impurities are present in the form of coarse constituent particles, i.e., Al7Cu2Fe, Al2CuMg, and Mg2Si [2, 3]. A major problem with 7XXX series alloy is that it is not fusion weldable. It is extremely sensitive to weld solidification cracking as well as heat-affected zone (HAZ) liquation cracking due to the presence of copper [4].

Friction Stir Welding (FSW) is an innovative solid state welding technique developed and patented at the welding institute (TWI) in 1991; this technique results in low distortion and high joint strength compared with other welding procedures, and is able to join all aluminium alloys, including series like 2XXX and 7XXX that are considered as virtually not weldable with classical liquid state techniques [5]. In FSW the work-piece does not reach the melting point and the mechanical properties of the welded zone (especially when attention is focused on heat-treatable light alloys) are much higher compared to those provided by traditional techniques. In fact, the undesirable low mechanical properties microstructure resulting from melting and re-solidification is absent in FSW welds leading to improved mechanical properties, such as ductility and strength in some alloys [6–8]. In this way, the welds are characterized by low distortion, lower residual stresses and absence of micro defects and then of retained products, dimensional stability.

Tianwen and Yanyao [9] conducted fatigue testing on AA 7075– T651 aluminium alloy under uniaxial, torsion and axial-torsion loading conditions and given a fatigue model which can predict the fatigue life for most experiments. Srivatsan et al.,[10] evaluated the fracture behaviour of aluminium alloy 7055 base material. Balasubramanian et al., [11] studied the effects of pulsed current and post weld ageing treatment on fatigue crack growth behaviour of AA 7075 aluminium alloy of 6 mm thick rolled plates using GTAW and GMAW processes and reported that the pulsing of current and simple post weld ageing treatment increased the fatigue crack growth resistance and fatigue life. Rubio-Gonzaleza et al., [12] were studied Dynamic fracture toughness of two structural materials. It was found that fracture initiation toughness of 6061-T6 aluminium alloy remains almost constant over different loading rates and different damage levels. For the AISI 4140-T steel, it was observed that the dynamic fracture toughness decreases as the damage level increases. The fracture toughness of Al6061-T6 was evaluated by

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indentation tests [13].Traditional compact tension (CT) tests were performed.

The accuracy of the indentation energy approach and a numerical analysis is adopted to investigate the stress state in the indentation test. The fracture toughness of AA6069-T6 and AA6061-T6 alloys hot extruded from air slip direct chill (ASDC) ingots were determined [14] by performing KIC and JIC tests. Dynamic fracture toughness and impact tests were performed [15] for cast A357 (Al–7Si–0.7Mg) alloy at various artificial aging conditions to evaluate the fracture toughness behaviour on the effect of artificial aging. Biju et al., studied [16] the electron beam welded AA2219 for the effect of base metal temper condition and mode of EBW on mechanical properties of the weld joint and fracture toughness at fusion zone (FZ) and heat-affected zone (HAZ) and compared with gas tungsten arc welded joints and those of the base metal. Results showed that EB welds have higher joint efficiency and fracture toughness than that of gas tungsten arc welding (GTAW). Fracture toughness of T6 base metal was found to be higher than its T87 counterpart. When welded, FZ and HAZ in T87 showed higher fracture toughness than that of T6; The tensile and fracture behaviour of as-cast and age-hardened aluminium AA 6063, silicon carbide particulate composites had been studied by Alaneme and Aluko [17].

However, the published information on the effect of post weld heat treatment on fracture toughness properties of Friction Stir Welded AA7075-T651 Aluminium Alloy is very scant. Therefore, this study aims to investigate the effect of post weld heat treatment on fracture toughness properties of Friction Stir Welded AA7075-T651 Aluminium Alloy joints. The resultant fracture toughness properties are compared with its friction stir welded fracture toughness properties.

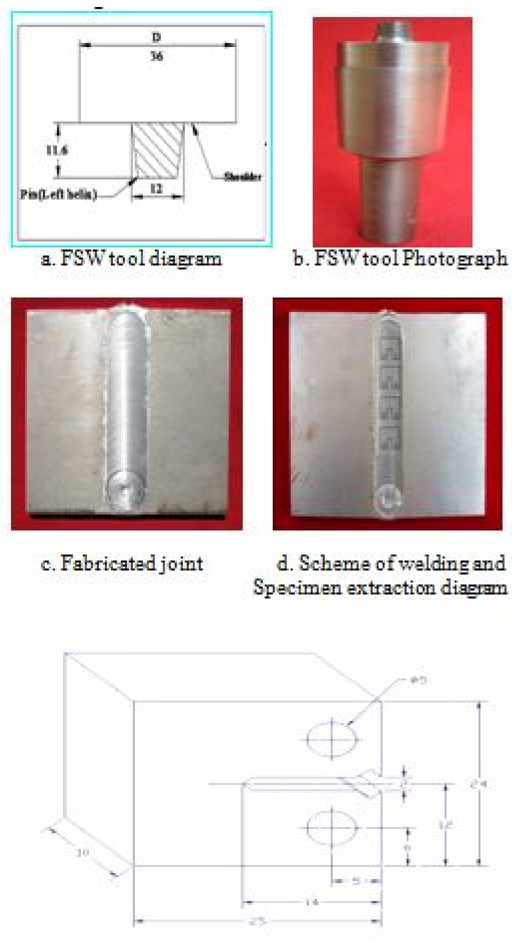
2. Materials and Experimental Procedure

In this investigation, rolled plates of 12 mm thick aluminium alloy (AA 7075 in T651 condition) were used to fabricate the joints. The chemical composition of parent metal is presented in Table 1. Fig.1 shows the experimental details. Fig. 1a and 1b represents the FSW tool diagram and tool photograph respectively. Prior to welding, the abutting faces of the plates were finely milled in order to avoid surface scaling intruded with the tool

Table 1 Chemical composition (wt %) of Aluminum Alloy AA7075-T651

Zn	Mg	Cu	Fe	Si	Mn	Cr	Ti	Al
6.1	2.9	2.0	0.50	0.4	0.30	0.28	0.20	Bal

The FSW tool with tapered threaded pin profile of shoulder diameter of 36 mm, pin diameter of 12 mm and pin length of 11.6 mm was used in this study. Few trial experiments were made to identify the parameters which give the defect free welds and those parameters were taken as the optimized welding parameters in this investigation.



a. FSW tool diagram b. FSW tool Photograph

c. Fabricated joint d. Scheme of welding and Specimen extraction diagram

e. Dimensions of fracture toughness specimen (All dimensions are in "mm")

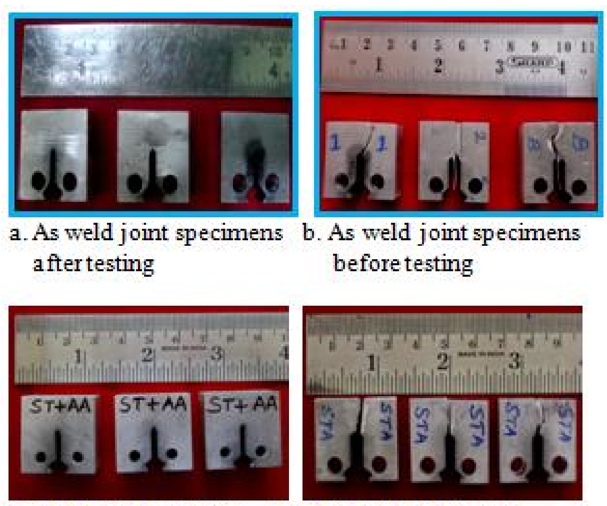
Fig. 1 Experimental details

Tool rotation and welding speeds were taken as 250 rpm and 25 mm/min respectively. Necessary care was taken to avoid joint distortion during welding. The welding was carried out normal to the rolling direction of the base metal. . After FSW, to study the effect of post weld heat treatment (PWHT) the weld joints were subjected to heat treatment cycle namely Solution treatment followed by water quenching and artificial ageing (STA).The As welded (AW) joints were not subjected to heat treatment after FSW. The STA treatment was carried out by solutionizing at 480° C for a soaking period of 60 min followed by water quenching and ageing at 120° C for a soaking period of 24 hrs. Fig. 1.c and d shows the fabricated joint photographs and schematic specimen extraction plan respectively and 1.e shows the dimensions of compact tension (CT) specimen.

The welded joints and STA joints were sliced using power hacksaw to prepare test specimens to evaluate the fracture toughness properties as per ASTM E-399 specifications. Fatigue pre-cracking was done in under uniaxial tensile loading condition (tension–tension mode) using clevis loading fixtures in servo hydraulic fatigue testing machine (Make: INSTRON, UK; Model: 8801) at 10 Hz and stress ratio 0.1. Pre-cracking was continued in three steps (machined notch length 12.8–13.3 mm, 13.3 – 13.8 mm and 13.8–14.3 mm at a maximum load of 1.1 kN, 0.9 kN and 0.8 kN respectively) at controlled laboratory environment. Monotonic loading for incremental crack growth continued for each programmed load-line displacement. This was followed by secondary fatigue cracking and loading till failure. Three specimens were tested to arrive at an average value for each category.

The KIC software was inbuilt in the machine for KIC testing. Crack opening displacement (C.O.D) gauge is attached with specimen for crack opening displacement measurement. For this type of loading, both the maximum and minimum loads are tensile and the load ratio, R = P min /P max, is in the range of $0 < R < 1$. A ratio of R = 0.1 is commonly used for developing data for comparative purposes. Cyclic loading may involve various wave forms for constant-amplitude loading. A measure of the resistance of a material to crack extension is expressed in terms of the stress intensity factor. Initially, the specimens were fatigue pre-cracked to either 0.1B or h or 1.0 mm, whichever is greater and then growing the pre-crack under given loading conditions (which includes frequency15Hz,load ratio 0.1,load amplitude 8 kN and initial crack size was 9 mm (a/w = 0.5).

Hardness measurement was done across the weld centre line by Vickers micro hardness tester (SHIMADZU, Japan Model: HMV-2T) with 0.05 kg load and 15 sec dwell time. The specimen for metallographic examination was sectioned to the required sizes from the joint regions and polished using different grades of emery papers. Final polishing was done using the diamond compound ($1\mu m$ particle size) in the disc polishing machine. Metallographic specimens were preper by standard metallographic technique and were etched with Keller's reagent (150 ml H2O, 3 ml HNO3 and 6 ml HF). The etching solution was cooled to 0°C and specimens were etched for about 20 s in order to study the grain structure of the weld zones and to allow for optical microscopy characterizations reveal the macro and microstructure. The micro structural analysis was done using optical microscope (MEIJI, Japan; Model: ML7100). For CT specimens it is recommended that thickness be within the range. Specimens having thickness up to the ratio of W/2 is employed. The (CT) specimens are prepared in longitudinal direction with notch and intended direction perpendicular to the rolling direction as per ASTM E-399 standards. Figure 2 shows the photographs of fracture toughness specimens of welded joints and STA joints before and after testing. The HRSEM analysis was carried out to identify the fracture mode of tested specimen.



a. As weld joint specimens after testing
b. As weld joint specimens before testing
c. STA joint specimens after testing
d. STA joint specimens before testing

Fig. 2 Photographs of fracture toughness specimens

3. Results

3.1 Tensile properties

The transverse tensile properties such as yield strength, tensile strength and percentage of elongation of AA 7075 alloy joints were evaluated. In each condition, three specimens were tested, and the average of three results is presented in Table 2 The yield strength and tensile strength of FSW joints are 335, 394 MPa respectively.

Table 2. Transverse tensile properties of as weld and STA joint.

	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 50mm gauge length (%)	Notch tensile strength (MPa)	Notch strength Ratio (NSR)
AW joint	335	394	12	410	1.04
STA joint	346	445	11	512	1.22

But the yield strength and tensile strength of STA joints are 510 and 563 MPa respectively. This indicates that there is a 30 % reduction in tensile strength due to FSW process.

3.2 Fracture toughness properties

The Table 3 shows the fracture toughness properties of the FSW joint and STA joint. The fracture toughness value of the FSW joint is 3 MPa√m less than that of the STA joint.

Table 3 Fracture toughness properties of as weld and STA joint

Specimen	Fracture toughness value (MPa√m)
FSW joints	25
STA joints	28

3.4 Microhardness

The hardness across the weld cross section was measured along the mid thickness of the joint using a Vickers microhardness testing machine and the results were presented in the graph Figure.3. The hardness profile shows basin like profile indicates that the stir zone undergoes softening due to the heat supplied by the FSW process.

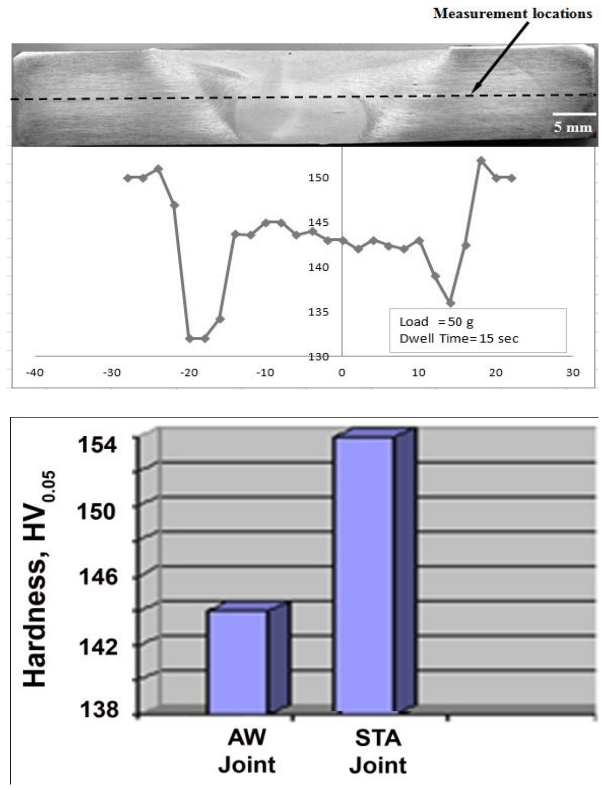
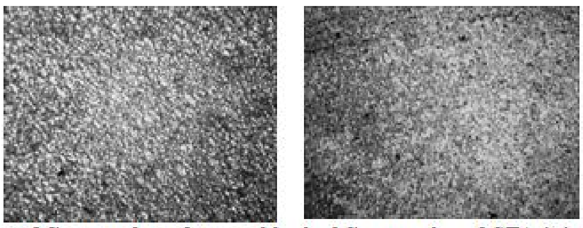


Fig. 3 Hardness profile along mid thickness

3.5 Microstructure

The figure.4a shows the optical microstructure of AW joint. After FSW, the NZ was characterized by a fine and equiaxed recrystallized grain structure. The recrystallized grain size was non-uniform along each of the three orthogonal directions of the wrought plate, resulting in an anisotropic microstructure. The microstructure of the welded joint normally divided into the following three regions: the dynamically recrystallized zone (DXZ) or the weld nugget, thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ) [18]. The weld nugget is characterized by a recrystallized, fine equiaxed grain structure because the precipitates have fully or partially gone into solution and re-precipitated during the joining process. The transition zone between the heat-affected zone (HAZ) and the weld nugget is thermo mechanically affected zone (TMAZ) characterized by a highly deformed structure [19].



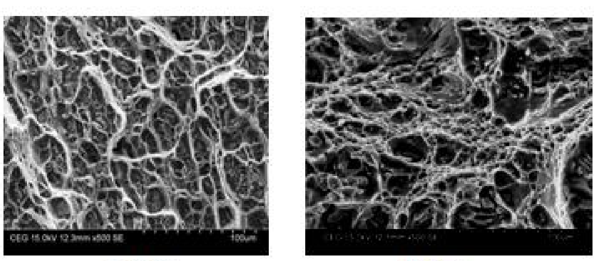
a. Micrographs of as weld joint of stir zone. b. Micrographs of STA joint of stir zone.

Fig. 4 Micrographs

The pre-crack is initiated in the weld nugget only. So, in this article weld nugget zone microstructure only have been discussed. The weld nugget is composed of fine-equiaxed recrystallized grains, which are formed under the high temperature and high rate of deformation in the weld nugget due to the pins stirring [15], and the size of the crystal grain is very fine. The solutionising treatment involved in the STA joint caused an increase in grain size of the NZ refer Fig. (4b).

3.6 Fractographs

Fig. 5 shows the SEM micrographs of the fracture surface of the final failure region (FF) region (where unstable crack growth occurs) of the as weld and STA joints. From the fractographs it is observed that the tear dimples are elongated along the loading direction and this is mainly because of the limit load condition at the time of final fracture. Even though unstable crack growth occurs in the final failure region, the final fracture is still in the ductile mode and it is evident from the presence of dimples. But the shape and size of the dimples are different in the FSW and STA joints and it is controlled by grain size and strengthening precipitates size. The elongated and coarse dimples were observed in as welded joint (figure 5a). Fine dimples were seen in as STA joints (figure 5b). This indicates that the resistance offered by STA joint for the growing fatigue crack, even in the unstable crack growth region is much better than AW joints.



a. FSW b. STA

Fig. 5 Fracture surfaces of final failure region of CT specimen

4. Discussions

The reasons for the poor fatigue crack growth resistance of the as welded joint compared to the STA joints are inferior tensile properties of the joints. The lower elongation in the FSW joint imparts lower resistance to the fatigue crack growth and hence higher fatigue crack growth rate is observed in FSW joint compared to the STA joint. It is a general tendency that the fatigue crack growth resistance simply becomes greater as the tensile strength or the yield strength obtained from the static tensile test becomes greater, because the plastic strain per load cycle is reduced. The yield strength has a major influence on the fatigue crack behavior of as weld joint. Lower yield strength and lower micro hardness of the as weld joint resulted in inferior fatigue crack growth resistance when compared to the STA joint. [11]

Reduction in elongation (lower ductility) of the as weld joint also imparts lower resistance to fatigue crack propagation and hence fatigue crack growth rate is relatively high when compared to the STA joint. The combined effect of higher yield strength and higher ductility of the STA joint enhanced resistance to crack propagation and hence the fatigue performance of the STA joint is superior as compared to as welded joint. The microstructure of the weld region (stir zone) also plays a major role in deciding the properties of friction stir welded AA7075-T651 alloy. Mechanical properties of FSW joints depend on structural characteristics of weld region, which in turn depends on the specific thermal / mechanical cycles imposed during friction stir welding. Fine equiaxed grains in the stir zone imply that dynamic recrystallization has taken place during welding due to plastic deformation at elevated temperature. In heat treatable alloys, the static properties of the friction stir welds are dependent on the distribution of strengthening precipitates rather than the grain size. [21] Hence, from the above discussion it can be concluded that inferior tensile properties, reduced hardness, dissolution of precipitates are the main reasons for lower fatigue crack growth resistance of FSW joint compared to its STA joint.

5. Conclusions

The fracture toughness value of friction stir welded 12 mm thick AA7075-T651 aluminium alloy joints were evaluated and compared with STA joint value. From this investigation the following important conclusions are derived:

1) Friction stir welded AA 7075-T651 alloy joints exhibited 70% joint efficiency i.e., tensile strength of the AW joint is 30% lower compared to STA joint.

2) The fracture toughness value of the FSW joint is 3 MPa√m less than that of the STA joint.

Though AW joint have recrystallized finer grains at the stir zone, the yield strength, notch tensile strength and hardness are lower. This may be due to dissolution of precipitates during friction stir welding which needs further investigation.

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