



FRACTURE TOUGHNESS OF FRICTION STIR WELDED ALUMINIUM ALLOY

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ABSTRACT

The fracture toughness of dissimilar aluminum alloys butt-joined by Friction Stir Welding (FSW) is studied. The aluminum grades used in this project were 5083 and 6061. The feasibility of using conventional belt-driven milling machine to perform FSW was also investigated by adding a custom-made compact clamping jig and FSW tool bit to the machine set up, and by varying machine parameters such as tool rotational speed (ω , rpm), tool traverse speed (v , mm/min), plunge depth (mm) and tool tilt angle. Preliminary FSW runs were done with the milling machine to modify it for the purpose of FSW. Two types of test were carried out which were tensile test and single edge notch tension (SENT) test. Both tests were performed on a Universal Testing Machine (UTM). By visual inspection, tunnel defect was seen in SENT specimens and in the dissimilar grade FSW joint for tensile testing specimen. The similar grade FSW joints performed less than their base material in terms of tensile strength. The critical stress intensity factor (SIF) for the welded specimens were found to be lower than critical SIF values known from literature for their respective materials.

Keywords: fracture toughness, friction stir welding, aluminum, SENT.

INTRODUCTION

Metal has become one of the most valuable things in modern day construction, vehicle industries, steel pipes [1] and others. Steels are widely used in these industries due to its excellent strength and toughness, although recent advances in aluminum alloying has made it a much more attractive choice due to its light weightness as opposed to steel [2, 3]. This is most important for vehicle industries where weight influences fuel consumption thus attractiveness of the vehicle, although a few disadvantages of lightweight aluminum alloys need to be properly addressed [4]. As the structure gets bigger and more complex, a joining technique is needed to hold the structure together firmly. One such joining technique is Friction Stir Welding, invented in 1991 at The Welding Institute (TWI), Cambridge, United Kingdom [6], where it is a solid state process that produces welds for materials that are hard to weld such as aluminum.

Ship classification societies have always recognized fracture toughness as a key material property [8]. The influence of fracture process can be divided into two sets of conditions where the first set is global conditions which involve geometry, loading material, and environment, while the second set is local conditions that consist of the flaws and material imperfections encountered in the neighborhood of the fracture path [9].

This paper contains the study done on the fracture toughness of butt-joined FS Welded Aluminum Alloy 5083 and 6061. FSW was done using a belt-driven milling machine to investigate the flexibility of the welding process. Custom jigs and tool bit were added while parameters such as tool rotational speed, travel speed, plunge depth and tilt were varied to fit the milling machine for FSW purposes. Tensile testing and Single Edge Notch

Testing (SENT) were done on welded specimens using Universal Testing Machine (UTM).

EXPERIMENTAL PROCEDURE

A. Materials and set up

The aluminum alloys welded in this experiment were Aluminum Alloy 5083 and 6061 plates cut to dimensions that would fit into the clamping jig used (refer Figure-1 and Figure-2). All plates are of thickness 5mm. H13 tool steel hardened to 50HRC was used as the FSW tool with dimensions of shoulder diameter of 20mm, pin diameter of 5mm and pin length of 5mm (refer Figure-3). Clamping jig was fabricated out of mild steel.

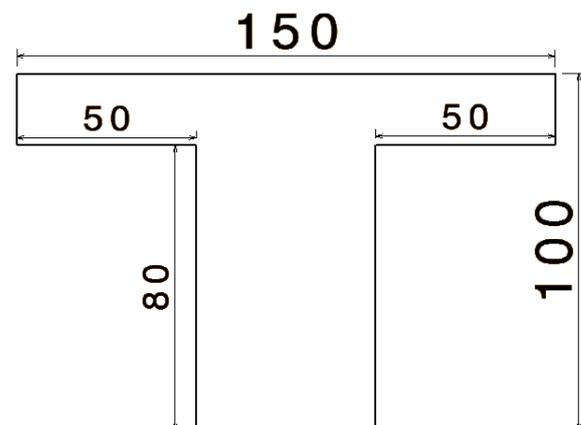


Figure-1. Dimensions of aluminum plates used for welding.

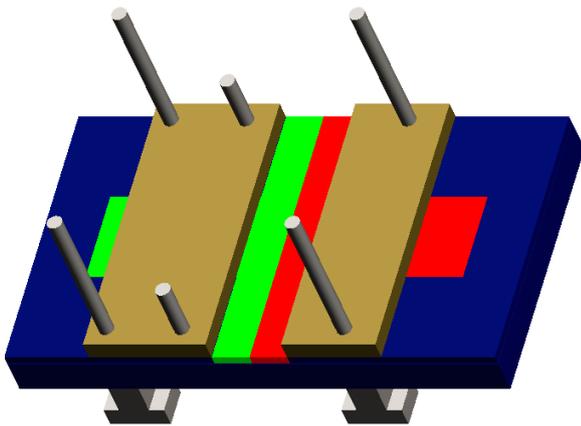


Figure-2. 3D CAD of clamping jig

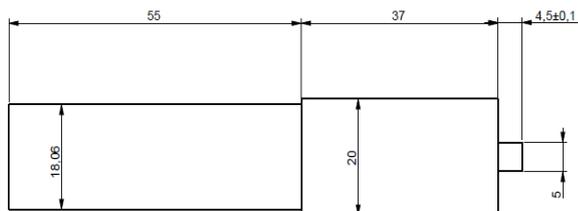


Figure-3. Dimensions of FSW Tool Bit.

The FSW tool was used in place of a milling bit to fit the machine for FSW functionality. The clamping jig was designed to be compact in order to reduce material waste that commonly occurs when cutting large weldpieces that use big conventional clamping jigs. The jig was designed such that the final weldpiece's dimensions are close to the required dimensions for testing (tensile, SENT). FSW butt-joints between similar grades (Al 5083-Al 5083, Al 6061-Al 6061) and dissimilar grades (Al 5083-Al 6061) were produced. Weldpieces were then cut by Wire Cut EDM into testing specimens for both tensile and Single Edge Notch testing (SENT). Standard dimensions for tensile testing specimens follow ASTM370-14[10] while SENT specimens adhere to suggested dimensions by Anderson [11].

B. Preliminary experiment and FSW

Preliminary experiments were done to find suitable FSW parameters. These parameters were tool rotational speed (rpm), traverse speed (mm/min), plunge depth (mm) and tilt angle (deg). The milling machine used to perform FSW was a MASTIKA belt driven milling machine. It has 16 speeds to choose from as shown in Figure-4. From preliminary runs, a spindle rotational

speed of 1100rpm was chosen as it resulted in welds with no visual defects.



Figure-4. The spindle speeds to choose.

The tool traverse speed was chosen as 36 mm/min. The tool plunge depth chosen was 4.6mm which was 92% of the thickness of the workpiece. Clamping jig was used to hold the two workpieces that were to be welded.

C. Tensile test and SENT test

SHIMADZU TCE-N300 Universal Testing Machine was used to perform both tests. Specimens were cleaned of grease or oil prior to mounting on testing machine to ensure proper gripping by the machine clasper thus preventing slippage. An extensometer was used to measure the local change of length of tensile specimens under applied stress. This provides the strain data used in stress-strain plots. The extensometer was attached to the specimen as shown in Figure-5. The extensometer used has a gauge length of 50mm.

RESULTS AND DISCUSSIONS

The collected data from both tests are used to evaluate the critical stress intensity factor (SIF), K_{IC} on similar joints of Al 5083-5083, Al 6061-6061 and the dissimilar joint of Al 5083-6061. The data collected is also used in evaluating the performance of the FSW setup used in joining the specimens.

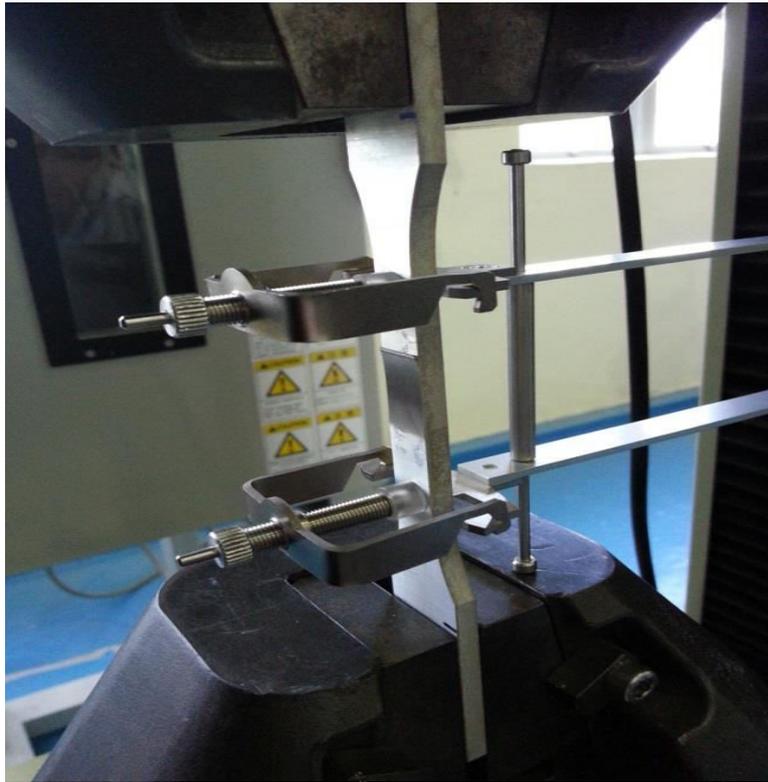


Figure-5. Set up of extensometer on a tensile specimen mounted on UTM.

A. Stress and strain

The cross-sectional area of each tensile specimen tested is constant at 62.5mm^2 . The calculated stress and

strain and their respective average values are shown in the Table-1 and Figure-6.

Table-1. Calculated max stress (MPa), max strain (%), and the respective average value in tensile test.

Specimen joined (Aluminum alloy)	Specimen number	Max stress, MPa	Max strain, %
5083-5083	1	145.50	2.45
	2	162.85	2.64
	Average	154.175	2.54
6061-6061	1	137.30	1.35
	2	101.70	0.67
	Average	119.50	1.01
5083-6061	1	86.20	0.46
	2	70.05	0.16
	Average	78.125	0.31

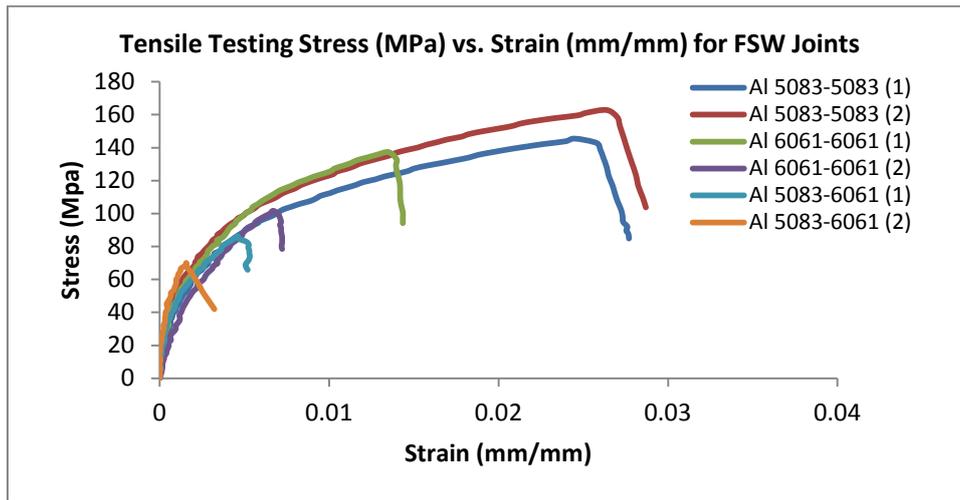


Figure-6. Stress vs. Strain curves for FSW tensile specimens.

After compiling data from each test in a single plot as show in Figure-6, it is seen that similar FSW joint of Al 5083-5083 had the highest maximum stress, followed by similar FSW joint of Al 6061-6061 and finally dissimilar FSW joint of Al 5083-6061.

From Table-2, for Al 5083-5083 specimen joined by FSW, the tensile strength is 32.38% less than the given value of tensile strength of Al 5083. As for FSW Al 6061-6061 specimen, a drop of 17.59% with respect to the given value of tensile strength of Al 6061 was seen.

Table-2. Comparison between experimental tensile strength of FSW joints and known tensile strength.

Specimen joined (Aluminum alloy)	Average max tensile strength after FSW (MPa)	Given tensile strength value (MPa)	% Difference
5083-5083	154.18	228	32.38
6061-6061	119.50	145	17.59

B. SENT tests

The cross-sectional areas for each specimen joined are kept constant which is 200mm². Since the value of maximum applied force is obtained from experiment, value of calculated maximum stress is presented in Table-3.

Table-3. The calculated max force and max stress for SENT test.

Specimen joined (Aluminum alloy)	Max force, kN	Max stress, MPa
5083-5083	10.8313	54.15625
6061-6061	11.6563	58.28125
5083-6061	12.3653	61.82815

Stress against displacement curves for the FSW SENT samples were compiled in Figure-7. When comparing the results obtained, dissimilar FSW joint of Al 5083-6061 recorded the highest stress value at 61.82815MPa followed by the similar FSW joint of Al

6061-6061 and Al 5083-5083 at 58.28125MPa and 54.15625MPa respectively. This means the dissimilar joint of Al 5083-6061 recorded the highest critical stress intensity factor.

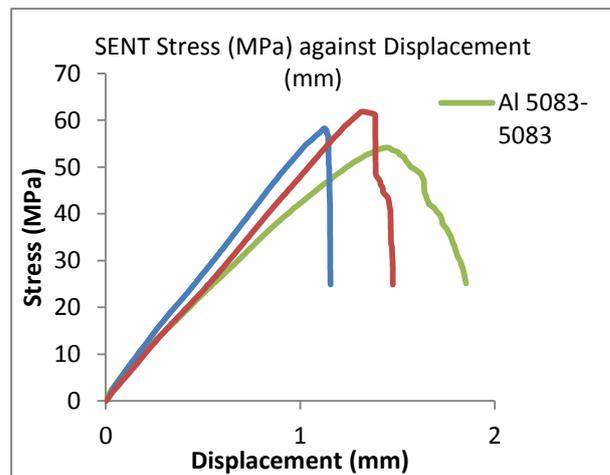


Figure-7. Stress vs. Displacement curves for FSW SENT specimens.



C. Critical stress intensity factor, K_{1c}

The equation used to calculate the critical stress intensity factor for each joined specimen is:

$$K_{1c} = f\left(\frac{a}{W}\right) \sigma_{max} \sqrt{a} \tag{1}$$

where $f\left(\frac{a}{W}\right)$ is the corrective factor and is defined as follows:

$$f\left(\frac{a}{W}\right) = 1.12\sqrt{\pi} - 0.41\frac{a}{W} + 18.7\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4 \tag{2}$$

Equation (5) then becomes:

$$K_{1c} = \sigma_{max} \sqrt{a} \left[1.12\sqrt{\pi} - 0.41\frac{a}{W} + 18.7\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4 \right] \tag{3}$$

where σ_{max} is the maximum stress recorded and $\frac{a}{W}$ is the ratio of crack length, a to width of the specimen, W .

Since the ratio of crack length, a to width of specimen, W are kept constant at 0.25, the corrective factor $f\left(\frac{a}{W}\right)$ is calculated to be 2.660499875.

The value of critical stress intensity factor, K_{1c} for each specimen can be calculated since all the parameters in Equation (1) are now known and the result is presented in Table-4.

Table-4. Comparison between experimental critical SIF and known critical SIF values.

Specimens joined (Aluminum alloy)	Calculated K_{1c} , $MPa\sqrt{mm}$	Calculated K_{1c} , $MPa\sqrt{m}$	Given K_{1c} , $MPa\sqrt{m}$	% Difference
5083-5083	455.63	14.408	43	-66.49
6061-6061	490.33	15.506	29	-46.53

Referring to Table-4, when comparing the experimental value of critical SIF to the known given value of critical SIF through [12], [13], and Glomac, it is seen that a similar FSW Al 5083-5083 joint recorded a critical SIF value that is 66.492% less than its base material's known critical SIF value. FSW Al 6061-6061 joint had a value that is 46.532% less than its base material's.

D. Defects and errors

A few defects were found on the FS Welded samples. No tunnel defect can be seen on the similar FSW joints of Al 5083-5083 and 6061, but tunnel defect can be seen on the dissimilar Al 5083-6061 joint. In addition, tunnel defect is present on all SENT specimens. The presence of these tunnel defects influenced the crack path as can be seen on the SENT sample of Al 5083-6061 (Figure-10). Several factors could contribute to the formation of a tunnel defect. Stirred plasticized metal needs to fill the small gap of two different pre-specimens. When the traverse speed is too fast, the plasticized metal does not have sufficient cooling time to cover the gap. The following mathematical model was proposed by Zhang *et al.* for defect volume in FSW [14]:

$$P\omega/v \geq V/k(r_{sh} - r_p) \tag{6}$$

P is pressure, ω is tool rotation speed, v is tool travel speed, V is volume of void, k is a proportion factor related to metal properties, r_{sh} is tool shoulder radius and r_p is tool pin radius. In this model, the left hand side represents the time that the tool spent in pressing

plasticized material into any pores or voids in the weld. The right hand side represents the time required to fill the voids. According to the model, in order to avoid tunnel defects, the filling action of the tool must be strong enough to fill any voids present during welding. As can be seen in this model, a higher heat input contributes to stronger filling action of the tool. This is achieved by increasing ω or decreasing v .

The FSW tool design also plays a role in preventing tunnel defects. Features are added to the tool such as concave/convex and grooved shoulder, while threads are commonly added on the pin. These features are used to increase stirring motion, such that plasticized material in front of the tool can be pushed towards the back, essentially filling voids left by the tool pin. Dehghani *et al.* found that the tool pin diameter itself plays an important role in defect prevention [15]. A smaller tool pin leads to smaller voids, thus leading to lesser volume that the plasticized material pushed by the shoulder needs to fill into.



Figure-8. Tensile specimens from top to bottom: Al 5083-5083, Al 6061-6061, Al5083-6061.



Figure-9. SENT specimens from top to bottom: Al 5083-5083, Al 6061-6061, Al 5083-6061.

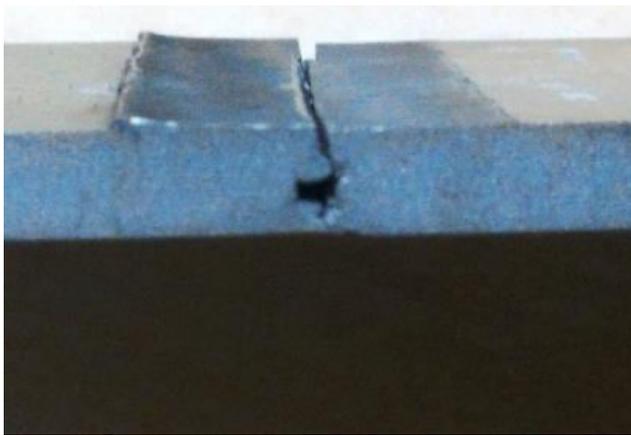


Figure-10. Tunnel defect in SENT specimen of Al 5083-6061.

CONCLUSIONS

Friction stir welding was performed on a belt-driven milling machine to produce similar and dissimilar grade butt-joints between aluminum alloy 5083 and 6061. Parameters chosen to perform FSW were tool rotational speed of 1100 rpm, tool travel speed of 36 mm/min, plunge depth of 4.6mm and tilt angle of 3°. Weldpieces were cut to samples for Tensile and Single Edge Notch Testing to calculate the critical stress intensity factors. It was found that critical SIF values of all FSW samples were similar to each other, with similar FSW Al 5083-5083, Al 6061-6061 and dissimilar FSW Al 5083-6061 recording K_{IC} values of 14.408 $\text{MPa}\sqrt{\text{m}}$, 15.506 $\text{MPa}\sqrt{\text{m}}$ and 16.45 $\text{MPa}\sqrt{\text{m}}$, respectively. By comparison, the K_{IC} values of similar FSW aluminum grades were lower than the known K_{IC} values of their respective grades. A FS Welded Al 5083-5083 had K_{IC} of 14.408 $\text{MPa}\sqrt{\text{m}}$ as opposed to 43 $\text{MPa}\sqrt{\text{m}}$. A FS Welded Al 6061-6061 had K_{IC} of 15.506 $\text{MPa}\sqrt{\text{m}}$ while the known K_{IC} value for Al 6061 is 29 $\text{MPa}\sqrt{\text{m}}$.

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