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Fracture Toughness and Fatigue Crack Growth Study of Friction Stir Welded Plates

Siti Nur Farhin Mokhtar, Azmi Abdul Wahab and Saravanan Karuppanan
Department of Mechanical Engineering, Universiti Teknologi PETRONAS,
31750 Tronoh, Perak, Malaysia

Abstract: Friction stir welding has been demonstrated as a viable replacement to conventional fusion welding in various engineering applications. In most cases, the suitable welding parameters were selected based primarily on the tensile tests performed on welded test joints. In this project, a study on Fracture Toughness (FT) and Fatigue Crack Growth (FCG) of friction stir welded A6061 plates of 10 mm thickness will be performed. The tests were conducted according to ASTM Standard Test Methods E399-08 and E647-08. The objectives of the project are to perform Fracture Toughness and Fatigue Crack Growth tests on the plates, determining the plane strain fracture toughness K_{IC} and the rate of fatigue crack growth of the A6061 welded plates and comparing those properties with non-welded A6061 plates. Friction stir welding was conducted using CNC milling machine. The sample plates were fabricated into Compact Tension (CT) specimen configuration using EDM machine. To meet the requirement of sharp notch, precracking was conducted for about 30,000 cycles using a cyclic frequency range of 0.3-4.0 Hz with precracked crack lengths of around 25.2 mm. FT tests were conducted using 0.01 mm sec^{-1} stroke rate. FCG tests were conducted using the same cyclic rate range with fatigue precracking, with a stress ratio of 0.1. The results indicated that the friction stir welded plates exhibited lower fracture toughness and higher crack propagation rate than non-welded plates.

Key words: Friction stir welding, fracture toughness, fatigue crack growth

INTRODUCTION

Friction Stir Welding (FSW), which was introduced by The Welding Institute in 1991, has emerged as a promising alternative to conventional fusion welding. It bonds two or more plates by using a rapidly rotating cylindrical-shouldered tool with a threaded or non-threaded probe that travels along the joint line at a constant speed. The friction heat generated softens the stirred material without reaching the melting point of the alloy being joined (Sivashanmugan *et al*., 2010; Saad and Shibayanagi, 2007). The advantages offered by FSW have attracted many researchers who are now focusing on development of the technique especially in the application of lightweight alloys. Despite the widespread interest in the possibilities offered by FSW, data concerning the mechanical behavior of joints obtained using this process is still scarce.

In engineering design, the most basic concern to avoid structure failure is that the stress applied on the component must not exceed the material's strength. Moreover, in the presence of a crack, the component may be weakened and failure may occur at a much lower stress than normal. Fracture Toughness (FT) is a fundamental material property that depends on critical stress and crack length for crack propagation under static load. Plane-strain fracture toughness, K_{IC} is the crack-extension resistance under conditions of crack-tip plane strain in Mode I (opening mode) for slow rates of loading under predominantly linear-elastic conditions and negligible plastic-zone adjustments (Dowling, 1999). It is characterized by the material's resistance to fracture in a neutral environment in the presence of a sharp crack under essentially linear-elastic stress and severe tensile constraint. On the other hand, Fatigue Crack Growth (FCG) is a property concerning crack propagation caused by cyclic loading. Basically, the FCG test is designed to determine the rate of crack propagation. These are among the important variables that must be considered in designs involving welding.

In this study, the interest is to investigate these mechanical properties of FSW welded plates and compare them with the properties of non-welded A6061 aluminum plates. The tests involved are plane-strain fracture toughness and fatigue crack growth tests, which followed the American Society for Testing and Materials (ASTM) Standards E399-08 and E647-08 (ASTM E 399-90, 2008; ASTM, 1992). As recommended by both standards, the sample plates were fabricated into Compact Tension (CT) specimens. CT is a specimen configured with a single edge-notch which is loaded in tension. CT sample is

Corresponding Author: Siti Nur Farhin Mokhtar, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 31750 Tronoh, Perak, Malaysia

recommended because it is used for general purposes and requires the least amount of test material compared to others (ASTM E647, 2008).

The objectives of this study are to perform FT and FCG tests on the CT plates to determine the plain-strain fracture toughness, K_{IC} and the rate of crack propagation on FSW plates and evaluate the performance of friction stir welding at the chosen welding parameters and pin design. This study involved fracture toughness and fatigue crack growth tests on Non-welded (NW) and FSW welded A6061 plates with respect to ASTM Standards E399-08 and (ASTM E647, 2008) using CT specimens.

MATERIALS AND METHODS

Material properties and welding parameter: A6061 aluminum plates with 10 mm thickness were used this study. The chemical composition, mechanical properties and physical properties of A6061 are given in Table 1 and 2, respectively.

Plates of A6061 aluminum alloy with dimensions of 100×100×10 mm were joined by means of the FSW welding technique. The FSW welds were performed using the following parameters: welding speed of 12 mm min^{-1}; rotating speed of 1600 rpm; dwell time of 12 sec. A tool with a 6 mm diameter and a shoulder with 12 mm diameter was used.

Extensometer calibration: Prior to performing the tests, the modified extensometer must be first calibrated. The purpose of calibration is to verify the accuracy of the extensometer output, stimulate real-time testing and determine the correction factor of Crack Opening Displacement (COD). A micrometer was used to represent the crack mouth opening for the crack opening displacement.

Fracture toughness and fatigue crack growth tests: FT and FCG tests were carried out on NW and FSW welded plates using Universal Testing Mechanical machine equipped with a 100 kN load cell. The crack propagation was monitored indirectly with the compliance technique using a strain gage known as extensometer placed on the back-face of the specimen. CT geometry was adopted for NW and FSW welded plates. Straight-through notch was machined in specimens used for fracture tests in order to maintain plane strain conditions. The notch was placed at welding joint. The experiments were conducted in agreement with ASTM E399 and E647 standards. The experimental setup is outlined in Fig. 1.

Fatigue precracking task is the first step in the fracture toughness test where cyclical loading is applied

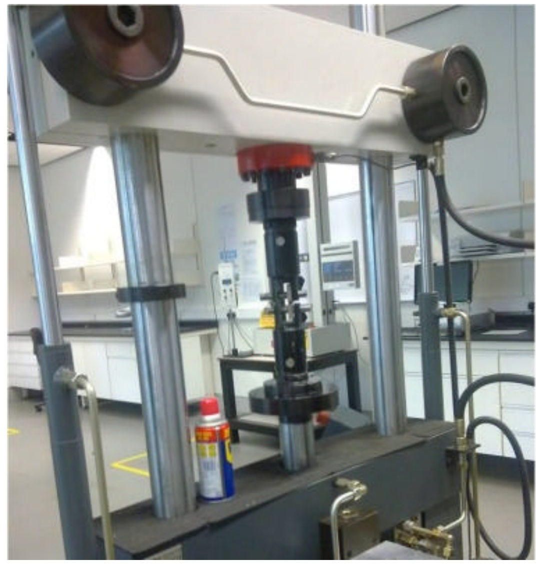

Fig. 1: UTM machine set up

Table 1: Chemical composition of A6061

Component	wt.%	Component	wt.%
Mg	0.8-1.2	Ti	Max 0.15
Cu	0.15-0.4	Fe	Max 0.7
Cr	0.04-0.35	Mn	Max 0.15
Si	0.4-0.8	Al	Balance
Zn	Max 0.25		

Table 2: Typical mechanical properties of A6061

Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Hardness (VHN)	Modulus of elasticity (GPa)
241	145	25	65	68.3

to the notched specimen for a number of cycles in stages to produce a sharp notch. The fatigue precracking task is divided into two stages where the total crack length will reach at least 20 mm in stage 1 and 25.5 mm at stage 2. The crack length is measured from the centerline of the holes. The cyclic load is applied by increasing slowly from 40 to 80% for the stage 1 and 10 to 60% for the stage 2. The maximum cyclic load to be applied is calculated using equation below by assuming $K_Q = 50\ MPa\sqrt{m}\ MPa\sqrt{m}\ MPa\sqrt{m}\ MPa\sqrt{m}$. for NW plate and $K_Q = 25\ MPa\sqrt{m}$ for FSW plate:

$$P_Q = \frac{K_Q B\sqrt{W}}{f\left(a/W\right)}\ P_Q = \frac{K_Q B\sqrt{W}}{f\left(a/W\right)} \quad (1)$$

FT tests were conducted using stroke rate of 0.01 mm sec^{-1}. Extensometer and load data were recorded during the tests. Subsequently, graphs of Load (kN) versus Crack Opening Displacement COD (mm) were generated. Values of P_Q were then determined by determining the intercept point of Load vs. COD line with linear lines of 95% of slope.

FCG tests were performed at $R = K_{min}/K_{max}$ equal to 0.1. FCG tests were run in lab condition at a frequency range of 0.3-4 Hz, under constant load amplitude (ΔK-increasing). Graphs of cyclic crack growth rate da/dN versus stress intensity range in log scale were generated. It has a linear relationship on a log-log plot:

$$\frac{da}{dN} = C(\Delta K)^m \tag{2}$$

$$\log\left(\frac{da}{dN}\right) = m\log(\Delta K) + \log C \tag{3}$$

where, m is the slope of the log-log plot and C is a constant. The behavior of crack propagation was presented by the slope of the graph.

RESULTS AND DISCUSSION

Fracture toughness test: Figure 2 and 3 show the relationship between load and COD for each sample. K_{IC} values were determined using the mathematical equation below:

$$K_{IC} = \frac{P_{max}\left[f\left(a/W\right)\right]}{B\sqrt{W}} \tag{4}$$

where, $P_{max} = P_Q$, B is plate thickness, W is the length from hole's center point to edge of the plate and f(a/W) is a dimensionless geometry parameter obtained from the equation below:

$$f\left(\frac{a}{W}\right) = \frac{\left(2+\frac{a}{W}\right)\left[0.886+4.64\left(\frac{a}{W}\right)-13.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.6\left(\frac{a}{W}\right)^4\right]}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}} \tag{5}$$

The summary of the fracture toughness tests is listed in Table 3-5 below. From the plotted graphs, we can see that NW plates yield quite similar values of P_Q with an average of about 8.69 kN. On the other hand, both of FSW plates yield the same P_Q value of 5.60 kN, which is lower than NW samples. Therefore, the calculated stress intensity ratio, K for NW and FSW plates are $26.4\ MPa\sqrt{m}$ and $17.0\ MPa\sqrt{m}$, respectively. This shows that FSW has lower fracture toughness, which is around 60% of NW samples, primarily because of the presence of wormholes along the joint lines. Besides, we can see also that each sample plate behaves differently during loading. The variation in the weld joint itself may contribute to the difference in fracture toughness curve obtained.

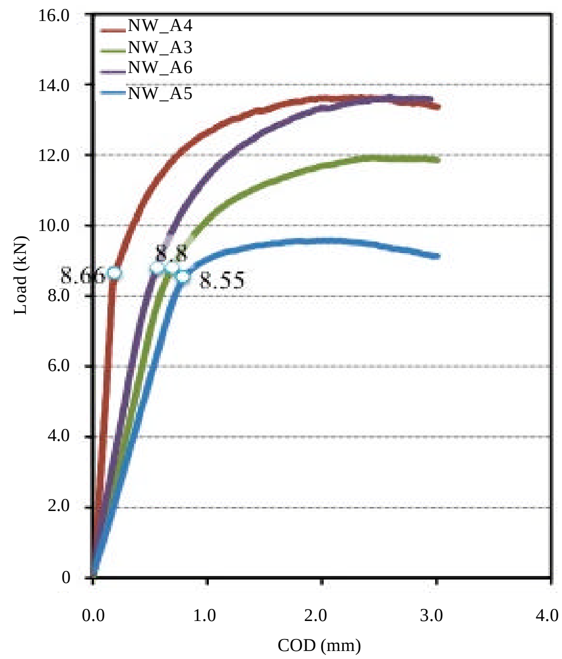

Fig. 2: Fracture toughness curves and PQ values for NW plates

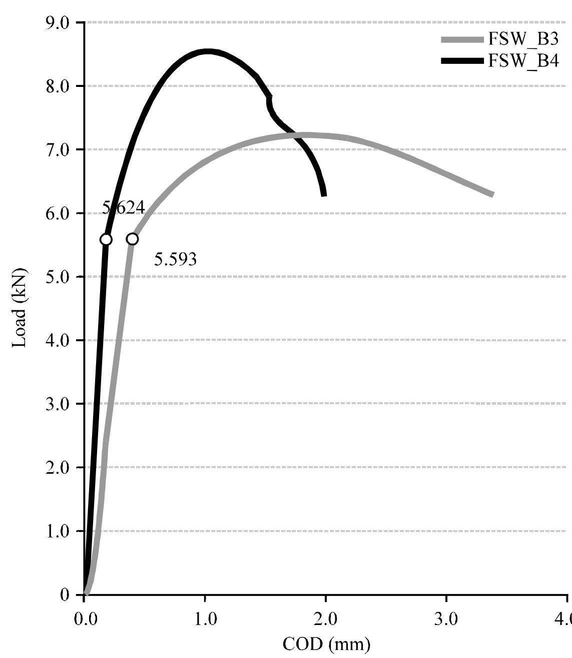

Fig. 3: Fracture toughness curves and P_Q (load) values for FSW plates

Table 3: Calculated fracture toughness values, K for both types of plates

Experiment details						Value
Temp. (°C)						22-23
Humidity (%)						66-68
Stroke (mm sec^{-1})						0.01
	Type of plates					
	NW				FSW	
	A3	A4	A5	A6	B2	B4
P_Q (kN)	8.80	8.60	8.55	8.80	5.60	5.60
P_{max} (kN)	11.91	13.61	9.57	13.61	7.21	8.54
K (MPa$\sqrt{m}$)	26.70	26.10	26.00	26.70	17.00	17.00

Table 4: Verification of K_{IC} validity, $P_{max}/P_Q = 1.10$

Sample plate	P_{max}/P_Q	K_{IC} validity requirement	Comment
NW A3	1.35	$P_{max}/P_Q \le 1.10$	Not valid
NW A4	1.58		Not valid
NW A5	1.12		Not valid
NW A6	1.55		Not valid
FSW B4	1.53		Not valid
FSW B2	1.29		Not valid

Table 5: Verification of K_{IC} validity

Sample plate	$2.5\left(\frac{K_{Ic}}{\sigma_s}\right)^2$	Validity requirement	Comment
NW A3	0.114	$0.025 \ge 2.5\left(\frac{K_{Ic}}{\sigma_s}\right)^2$	Not valid
NW A4	0.109		Not valid
NW A5	0.108		Not valid
NW A6	0.114		Not valid
FSW B4	0.046		Not valid
FSW B2	0.046		Not valid

Table 4 and 5 show the results of K_{IC} validity tests, which indicate that the tests failed to comply with K_{IC} validity requirements. This means that the calculated K values are not K_{IC}. This is because plane-strain fracture deals with brittle fracture where it is accompanied by no or little plastic deformation. It is a sensitive property which can only be determined if the sample plates are relatively thick where deformation in z-axis (which is perpendicular to the plate) is small and insignificant, i.e., $\varepsilon_z = 0$.

Fatigue crack growth test: Using the same sample configuration and set of test conditions, the relationship between cyclic crack growth rate da/dN and stress intensity range graphs were plotted as illustrated in Fig. 4 and 5 to describe the crack growth behaviors for both plates. Results for these tests are summarized in Table 6.

Since, ΔK increases with crack length during constant amplitude loading and the crack growth rate is dependent on ΔK, the growth rate is not constant but increases with the crack length. Assuming that the effects of environment and frequency are constant, ΔK values during cyclic loading serves the same function as K static loading. It characterized the severity of a combination of loading, geometry and crack length in propagation of cracks. From Table 6, we can see that the FSW has higher value for constant m compared to NW. This indicates that cracks propagate faster in the weld samples or in other words, the FSW sample has lower crack propagation resistance than NW sample.

Table 6: FCG test summary for both types of plates

Experiment details			Values
Temperature (°C)			22-23
Humidity (%)			66-68
Stress ratio			0.1
	Types of plates		
	NW	FSW	
	C1	D1	D2
Loading (kN)	7.408	6.318	4.544
C	5×10^{-13}	3×10^{-13}	8×10^{-14}
m	4.64	7.17	6.19

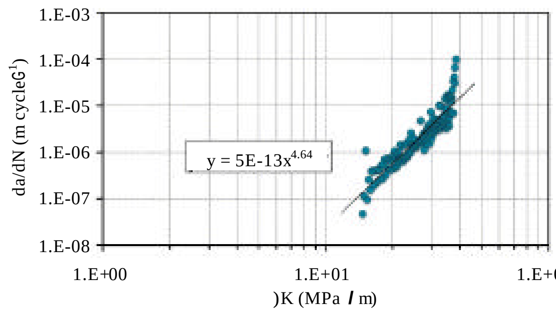

Fig. 4: Fatigue crack growth rates versus stress intensities for NW plates

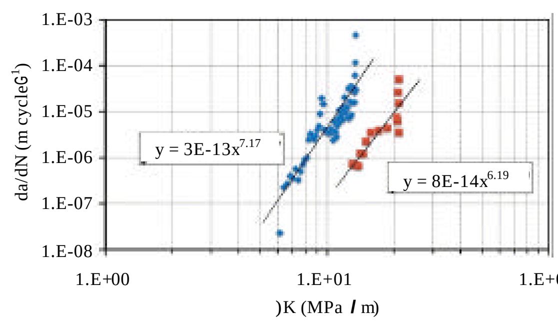

Fig. 5: Fatigue crack growth rates versus stress intensities for FSW plates

CONCLUSION

Based on the above results and discussions, the following statements can be drawn for 10 mm of FSW welded plates which was welded at rotational speed of 1600 rpm, weld speed of 12 mm min^{-1} and 12 sec dwell time, using tool pin of 8 mm length, 6 mm pin diameter and 12 mm shoulder diameter:

- The welded plate yields lower fracture toughness nearly 60% lower than the toughness of non-welded plates. The obtained K_Q is not the lowest K_Q (K_{IC})
- The crack growth is not dependent on load levels of components with the same geometry
- Cracks propagate faster in FSW welded plates than in non-welded plates

Further analysis can be done to get better understanding about the study. The following are some suggested recommendations for further enhancement of this study:

- New clevis with better accuracy and reduced tolerance, coupled with the use of a dedicated COD gage and calibrator should be fabricated
- Further studies on friction stir welding parameters and pin design: This is to optimize the welding parameters for better fracture toughness and fatigue crack growth properties, instead on just tensile properties
- Thicker specimen should be used for FT test although problems in preparing friction stir welded plate must first be addressed
- Microscopy on the surfaces of failed samples should be conducted to understand the mechanism of failure

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