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Investigation of Friction Stir Butt Welded Aluminium Alloy Flat Plates using Spindle Motor Current Monitoring Method

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Abstract

Friction-stir welding (FSW) is a solid-state joining process and used to join light alloy metals, which finds various industrial applications in aerospace, automotive and ship building, etc. Monitoring and control of friction-stir welding is essential for ensuring defect free and high strength welded joints. This paper presents spindle motor current monitoring approach for analyzing the weld tensile strength of friction stir welded components. Aluminium alloy of 6063-T6 plates with 4 mm and 6 mm thicknesses were joined by friction stir welding process using square, circular, triangular and conical tool pin profiles. The spindle motor current was measured by using a Hall Effect non-contact current sensor, which was interfaced with a data acquisition system. Measured current signals are useful to identify the different stages of friction stir welding process. Experimental results show a fairly linear trend between the tensile strength of welded joints and the percentage change in spindle motor current. Proposed method provides a simple approach for online monitoring of weld strength in friction stir welding process.

Keywords: Friction Stir Welding; Aluminium alloys; Tensile strength; Motor current monitoring; Current sensor.

1. Introduction

Friction stir welding (FSW) is a solid state metal joining process, invented at The Welding Institute (TWI), UK in 1991, in which a non-consumable rotating shouldered tool is plunged gradually into the butting faces of work pieces and navigated along the joint line [1]. The relative motion between the tool pin and the work plate generates frictional heat that develops a plasticized region around the tool and forms a solid-phase joint. The FSW process

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does not require consumables such as filler materials. The FSW process can be performed well in any orientation of work components, since gravity has no effect on the process. FSW appreciably reduces residual stresses compared to traditional welding techniques and creates tough and ductile joints with low distortion and shrinkage. FSW provides enhanced joint properties and performance, low deformation after welding, a major reduction in production costs and less skilled labour over conventional joining techniques [2]. FSW demonstrates good weldments on joining of aluminium alloys, steel, titanium and dissimilar alloys. This technique has been widely applied for welding aluminium alloys in aerospace, automotive and ship building industries [3].

Attempts have been made to investigate the effect of tool pin profiles and welding parameters on the tensile strength of weld joints in friction stir welding process. Influence of pin shape and the tool rotational speed have been analyzed on the friction stir processing and found that the weld parameters and tool pin shape play a major role in deciding weld quality [4]. An experimental study has been carried out to investigate the effect of tool rotational speed and pin profile on yield strength and elongation of the weld joints [5]. Experimental investigations were carried out to study effect of welding speed and tool pin profiles on aluminium friction stir welded butt joints [6]. The influence of tool pin profiles and welding speed on tensile properties of weld joint for dissimilar aluminium alloys was analyzed [7]. The influence of tool design on the mechanical properties and microstructure in friction stir welding was analyzed and found that the material flow and the quality of weld joints are primarily influenced by tool geometry and process parameters [8].

In order to assess the weld quality during welding process, various monitoring methods are proposed, in which application of motor current for process condition monitoring has been studied by number of researchers. In electrical monitoring methods, the stator current of an induction motor is used to monitor various kind of machine and process faults. The method of spindle motor current and voltage measurements were employed for online estimation of tool wear monitoring in milling operations [9]. This method of non-invasive and inexpensive electrical measurement increases the potential for industrial applications. Masaya et al. had developed a method of cutting force monitoring by current measurement, in which the monitoring of motor current is used to control the machine tool table position and cutting force in the feed direction [10]. Xiaoli had proposed a monitoring system for online tool breakage detection of small diameter drills by monitoring AC servo motor current [11]. The experimental results proved excellent online monitoring capability for tool failure. Also current measurement method had a low sensitivity to change of the process conditions and high success rate for the detection of the breakage of tools. Rajesh and Marimuthu had demonstrated a simple method for online drill wear monitoring and tool replacement decision-making using cutting current signals in drilling [12]. The effect of tool wear and process parameters with current signals were analyzed. These models on the relationship between current signals and the cutting parameters were established under different tool wear states. The real time tool condition was successfully analyzed using feed-motor current measured with inexpensive current sensors installed on the AC servomotor of a CNC turning centre [13]. Weglowski and Pietras developed a weld monitoring system to display the force and torque during friction stir processing of aluminium alloy 6082 [14].

It is observed from the literature that the motor power or current monitoring approach is feasible and inexpensive method of real-time monitoring in machine tools. However, its application in friction stir welding process is found to be limited. This work presents an experimental investigation on weld tensile strength of friction stir welded aluminium alloy components using spindle motor current based monitoring approach.

2. Experimental setup

In the present work, the friction stir welding experiments were carried out in a conventional milling machine with a vertical attachment, a rigid clamping fixture and an automatic feed control system. The schematic arrangement of the experimental setup is depicted in Fig.1. The milling machine spindle has a speed range of 45 to 2000 rpm and spindle motor power of 5 HP. In order to monitor the friction stir welding process, spindle motor current is measured using a Hall Effect sensor and the signal is acquired and stored in a personal computer based data acquisition system.

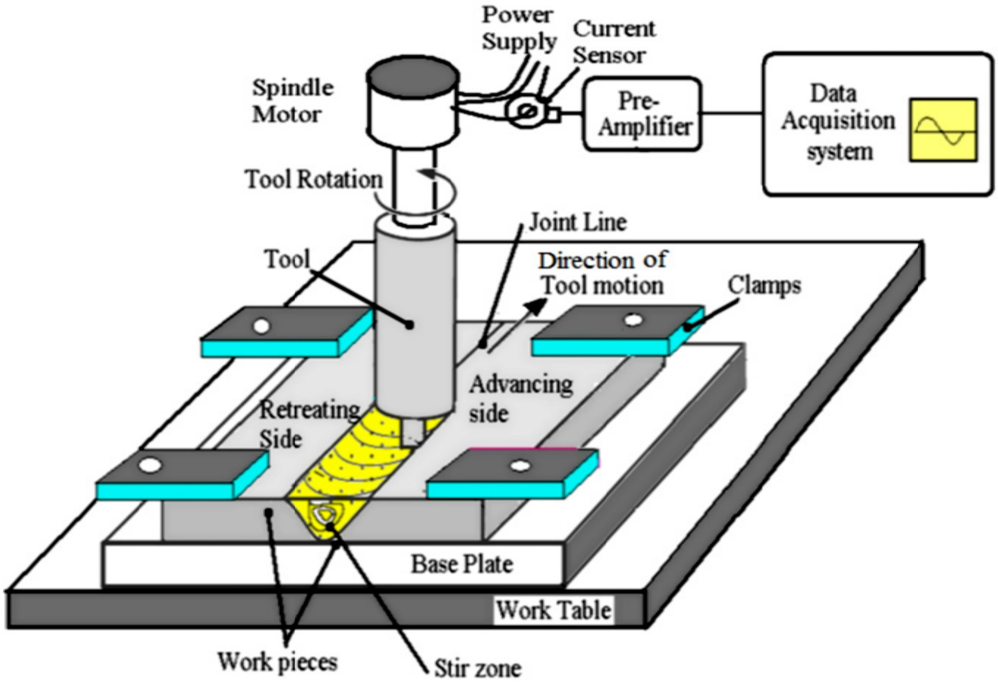


Fig. 1. Schematic diagram of FSW experimental setup

2.1. Work material

In this investigation, AA6063-T6 aluminium alloy plates of size 100 x 50 were used as the work material for butt-welding, which is widely used in architectural fabrication and furniture. The chemical composition and mechanical properties of AA6063-T6 are presented in Table 1 and Table 2.

Table 1. Composition of AA6063-T6

Elements	Al	Mg	Fe	Si	Cr	Cu	Mn	Ti	Zn
Wt %	97.5	0.8	0.35	0.4	0.1	0.1	0.1	0.1	0.1

Table 2. Mechanical properties of AA6063-T6

Parameters	Value
Ultimate tensile strength (MPa)	241
Tensile yield strength (MPa)	214
Hardness (HV)	83
Thermal Conductivity (W/mK)	200

2.2. Tool material and design

In order to investigate the effect of tool profiles on the weld tensile strength, experiments were carried out with circular, triangular, square and conical pin tool profiles. The friction stir welding tools were fabricated from stainless steel SS316 round bars. The chemical composition and mechanical properties of the cutting tool material are presented in Table 3 and Table 4.

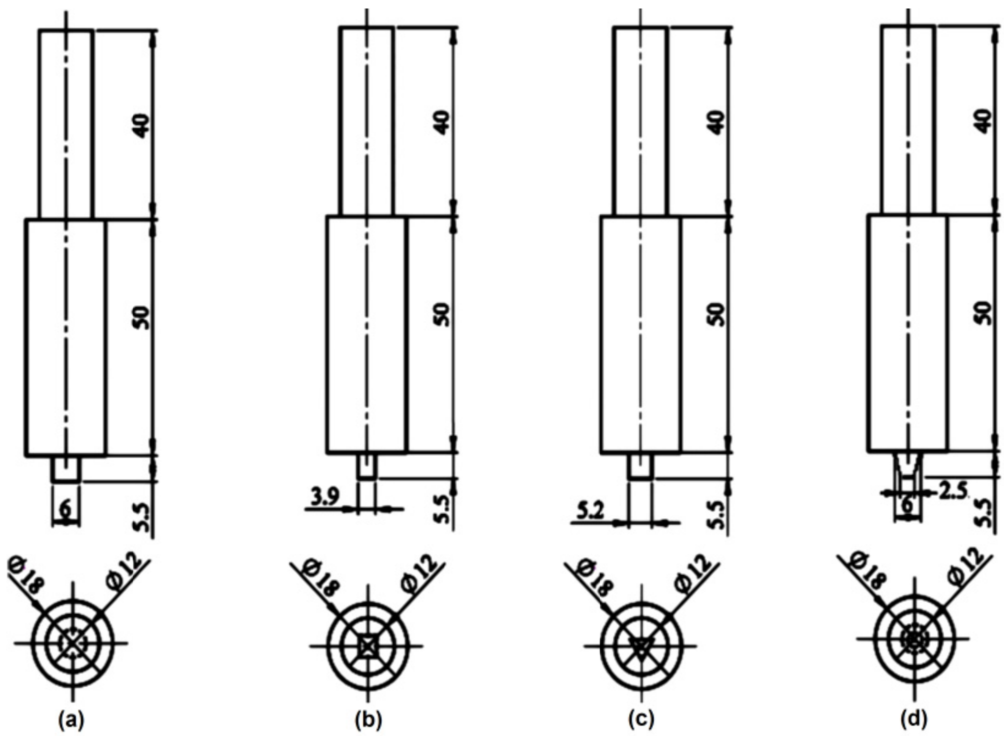
Table 3. Chemical Composition of SS316

Elements	Fe	C	Si	Mn	P	S	Cr	Mo	Ni
Wt%	45	0.008	0.75	2	0.045	0.03	17	2-3	12

Table 4. Mechanical properties of SS316

Parameters	Value
Ultimate tensile strength (MPa)	515
Tensile yield strength (MPa)	205
Hardness, Brinell	217
Thermal Conductivity (W/m.K)	16.3

Each tool has a pin profile, which is inscribed in a circle diameter equal to the work material thickness. The tool shoulder diameter was fixed as thrice of the pin diameter. The diameter of the tool pin was equal to the thickness of the work plates. The tool pin length was maintained 0.5 mm less than the work material thickness to accommodate the plunge depth during welding process. The schematic diagrams of different tools used in this experimental work are given in Fig. 2 with dimensions.



(Dimensions are in mm)

Fig. 2. Dimensions of FSW Tools (a) Circular Pin; (b) Square Pin; (c) Triangular Pin; (d) Conical Pin

2.3 Welding parameters

Single pass welding procedure was used to fabricate the butt joints. The friction stir welding consists of three stages. The rotating tool was made to contact with work plates freely for a period of 10 to 15 seconds to increase the heat energy by friction, which is known as preheating of work material. After pre-heating, plunge depth is increased to 0.3 mm gradually downwards and the rotating FSW tool was navigated along the work plates joint line with a feed rate of 40 mm/min by engaging automatic feed. The spindle speed is maintained at 1000 rpm during the welding process. Tool tilt angle is a parameter to improve the stuffing of the material by the tool shoulder. It will also help to eliminate surface defects. For aluminium welds, a tilt angle gives a notable change in the microstructure development and material flow. In the present work, tilt angle of the FSW tool was fixed as 2°.

2.4 Data acquisition system for spindle motor current measurement

The spindle is driven by a three phase induction motor with delta connection, which has a power rating of 3.7 kW of at 1460 rpm. The rated line current in spindle motor is 7 A at full load condition. The spindle motor voltage rating is 415 V. The experimental setup and sensor interfacing with data acquisition system is shown in Fig. 3.

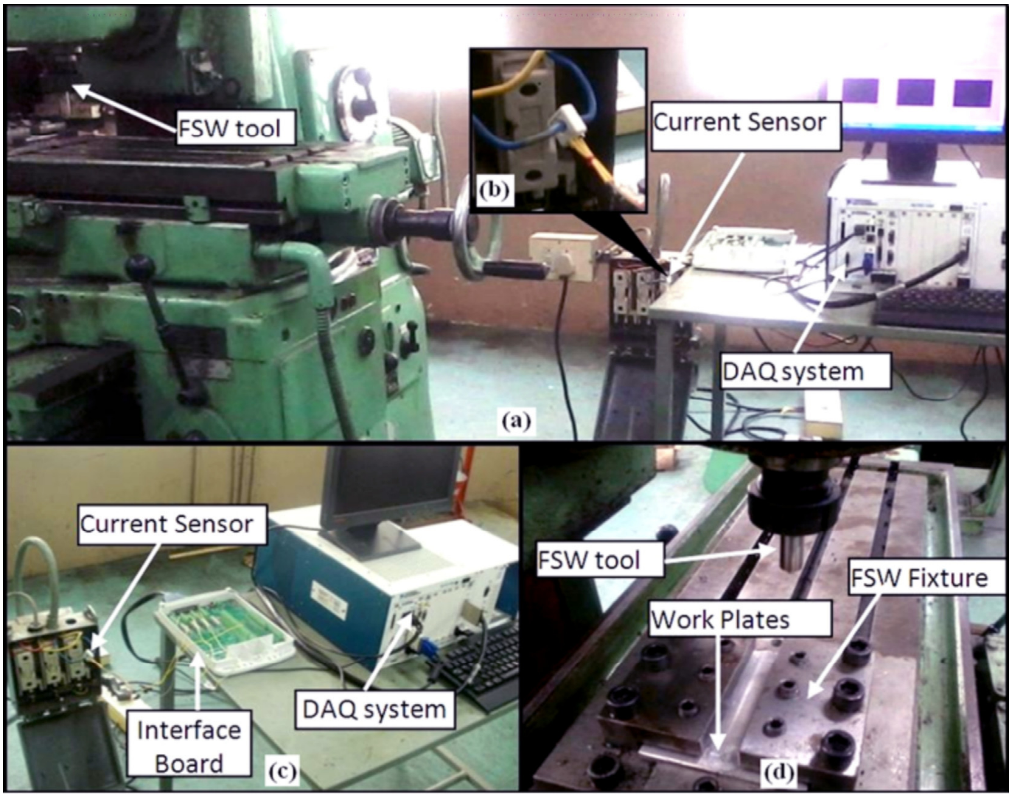


Fig.3. (a) FSW experimental setup; (b) Current sensor; (c) Data acquisition system; (d) FSW fixture and tool

A LabVIEW based data acquisition system was used for measuring the Root Mean Square (RMS) value of line current of the spindle motor. Non-contact Hall Effect current sensor of sensitivity 20 mV/A is utilized for this purpose. The line current of the spindle motor was recorded at various stages of the welding process. The sensor output is calibrated using the LabVIEW program to acquire the motor line current value in Amperes.

3. Results and discussions

3.1. Spindle motor current measurement and analysis

FSW tools with different pin profiles such as circular, square, triangular and conical shapes were used to butt weld the work material. Three experiments were conducted with each FSW tool. The RMS value of line current was measured over the weld period using data acquisition system. The spindle motor current measurements with different tools for welding 4 mm and 6 mm thickness aluminium alloy plates are shown in Fig. 4 and Fig. 5.

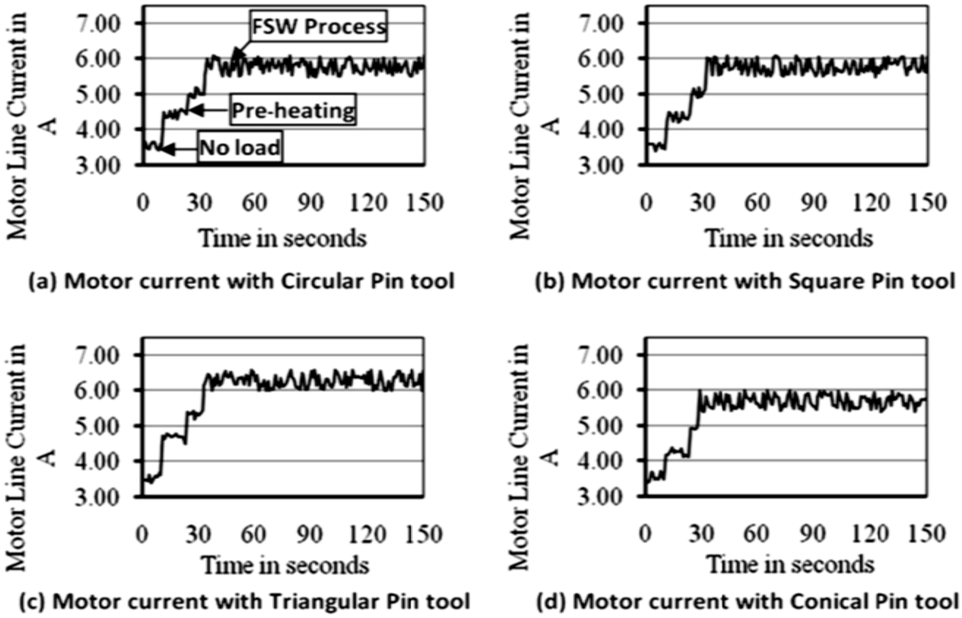


Fig. 4. Spindle motor current plots for FSW of 4 mm thick plates

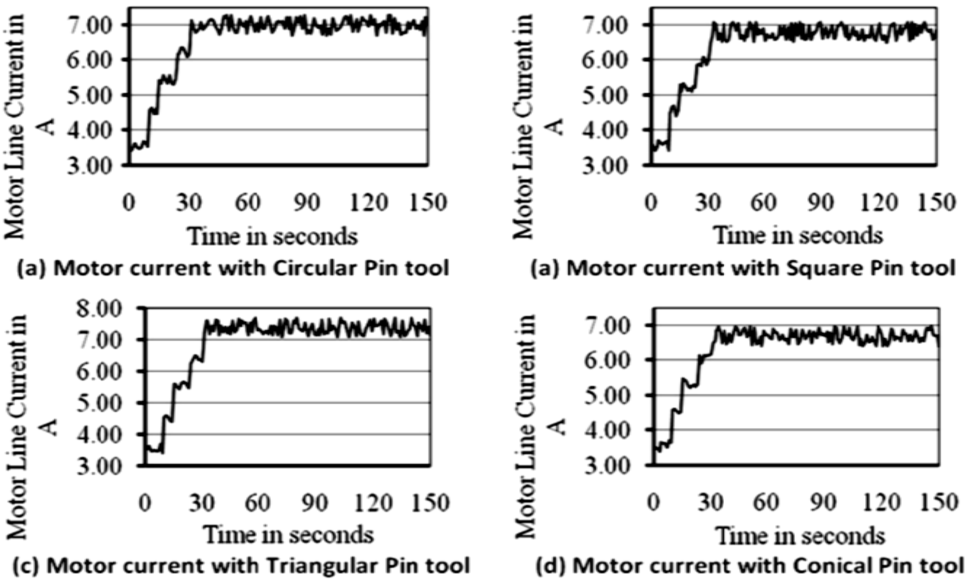


Fig. 5. Spindle motor current plots for FSW of 6 mm thick plates

The measurement of line current clearly identifies the different stages of friction stir welding process as shown in Fig. 4 (a). The current flow to the motor was found to be 3.5 A during no load condition, which occurs due to the inertia of the rotating spindle with FSW tool. There is an increase in motor current due to the increase in friction between the FSW tool and work material during the preheating stage. However, there is no appreciable change in the motor current during the welding process, as the work material is at plastic state due to the heat generated during the preheating stage.

Table 5 and Table 6 show the mean value of motor current during no load, pre-heating and joining process for each FSW tool profile to weld 4 mm and 6 mm thickness work plates respectively. It is observed that the magnitude of line current increases with increase in material thickness. It was found that the magnitude of line current for the process with square pin tool and conical are lesser than that of the FSW processes with circular and triangular pin tools.

Table 5: Motor current consumption during FSW of 4 mm thick plates

Pin profile	No load current (A)	Current at pre-heating (A)	Line current during welding (A)	% change in line current
Circular	3.5	4.35	5.61	60
Square	3.5	4.19	5.52	58
Triangular	3.5	4.62	6.07	73
Conical	3.5	4.28	5.60	60

Table 6: Motor current consumption during FSW of 6 mm thick plates

Pin profile	No load Current (A)	Current at Pre-heating (A)	Line Current during welding (A)	% change in line current
Circular	3.5	5.05	6.78	94
Square	3.5	4.93	6.58	88
Triangular	3.5	5.09	7.12	103
Conical	3.5	5.00	6.51	86

The percentage change in motor current flow current flow for each tool was calculated with respect to the no load condition of machine tool. The comparison of percentage change in motor current for different tool profiles and work plate thickness are shown in Fig. 6.

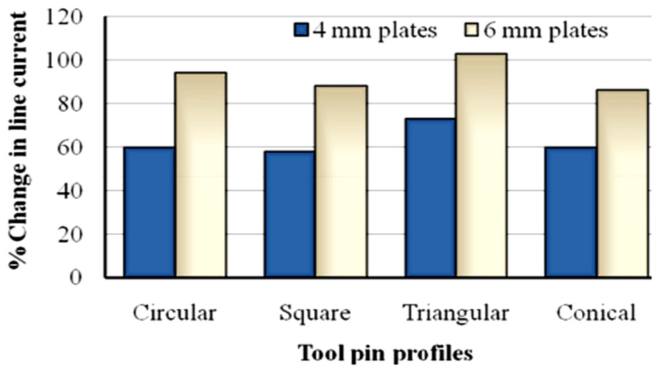


Fig.6. Comparison of change in motor current for different tool pin profiles and work plate thicknesses

The FSW of 4 mm thick plates shows spindle motor line current increase by 59%. The FSW of 6 mm thick plates has a spindle motor line current increase by 87%, causing the higher power consumption. When the material thickness increases the current flow also increases and causing more power input to the spindle motor. This increase is due to tool and work material contact friction during the friction stir welding process. The tool shoulder area and tool pin contact is also increases with work plate thickness.

3.2. Power consumption of friction stir welding process

In order to identify the tool profile, which offers energy efficient welding operation, the power input (P_{Input}) to the spindle motor is calculated from the line current using the following equation [15]:

$$P_{Input} = [\sqrt{3}\ V_L\ I_L \cos\theta] / 1000 \ldots\ \text{kW} \quad (1)$$

Where, V_L is line voltage of 415 V, I_L is line current measured using current sensor and Cos θ is the induction motor power factor of value 0.77. Table 7 shows the summary of power consumption during FSW of 4 mm and 6 mm thick plates.

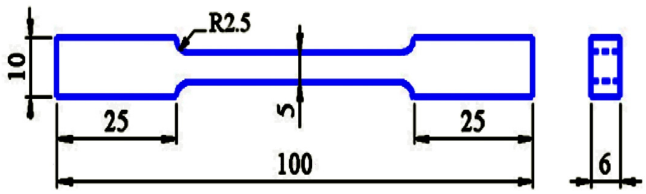
Table 7: Power consumption during FSW of 4 mm and 6 mm thick plates

Pin profile	Electrical power consumption for FSW of aluminium alloy plates (kW)	
	4 mm thick plates	6 mm thick plates
Circular	3.1050	3.7525
Square	3.0552	3.6419
Triangular	3.3596	3.9408
Conical	3.0995	3.6031

From the experiments, it was observed that the triangular pin tool creates considerably more motor current flow than the other tool types. The conical pin tool requires lesser amount of motor current, causing the less power consumption by the spindle motor. The conical shape assists easier material flow during the friction stir welding due to gradual decrease in cross section. It is inferred that the square profile consumes lesser power during welding of 4 mm plates. However, when the thickness is increased to 6 mm, conical pin profile consumes lesser power than other tool pin profiles.

3.3. Analysis of tensile strength of welded joint

Tensile test specimens were prepared from the friction stir welded joints using wire cut Electrical Discharge Machining (EDM), according to ASTM standard dimensions as shown in Fig. 7. The joints were visually inspected and found to be free from any external weld defects. A sample of a friction stir welded plate and tensile test specimen are shown in Fig. 8.



(Dimensions are in mm)

Fig. 7. Dimensions of tensile test specimen

Fig. 8. Weld sample and tensile test specimen (a) FSW specimen; (b) Tensile test specimens

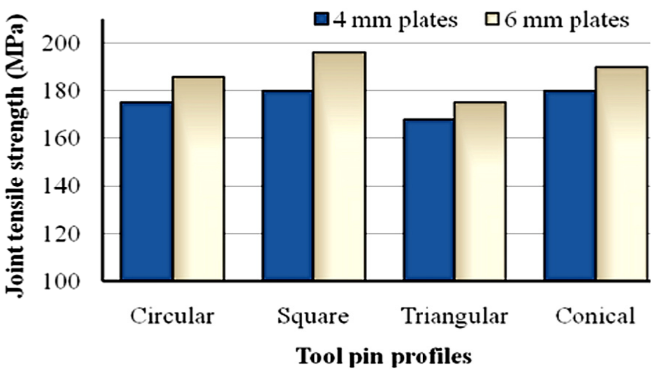


Fig. 9. Tensile strength of friction stir welded AA6063-T6 plates with different thickness

The transverse weld tensile strength of the friction stir welded work plates was evaluated using an electronic tensometer and the mean results of the trials are shown in Fig. 9. The square pin profile gives higher joint strength compared to circular, triangular and conical pin profile tools. This is due to more material flow caused by the pulsating action of the tool pin corners during the process. It is observed that the specimen obtained using the square pin profile tool has a maximum tensile strength of 196 MPa with 6 mm plate and 180 MPa with 4 mm plate. As the square tool pin has four flat faces, which enables higher pulsating flow of material than other tools. When the tool rotates at 1000 rpm, square pin produces 66 pulses per second as compared to 50 pulses per second by the triangular profile. This improves the flow of material and thereby improves the tensile strength of the specimen. The conical tool pin profile also shows good tensile strength next to square tool. The conical tool assists the material flow due to the shape. From the results obtained from the tensile testing, it is found that the tool pin profile has a significant effect on joint tensile strength of the FSW specimen.

3.4. Correlation of tensile strength with line current

The joint tensile strength and spindle motor current measurements were analysed for four different tools and two different materials thicknesses. Three welding trials were made with each tool for welding 4 mm and 6 mm thick aluminium alloy plates. The linear correlation analysis between the spindle motor current and tensile strength of the FSW joints was carried out and the regression equations are shown in Fig. 10. During friction stir welding process, work material reaches the plastic stage due to stirring action of the rotating tool. The tool pin profile influences material flow during FSW process, causing a change in spindle torque and influences the line current drawn by spindle motor. In addition, the material flow caused by tool pin profile leads to the changes in tensile strength of welded joints. Due to the variations in the tool profile, a decreasing trend is observed in joint tensile strength of work material with respect to the percent change in line current of spindle motor.

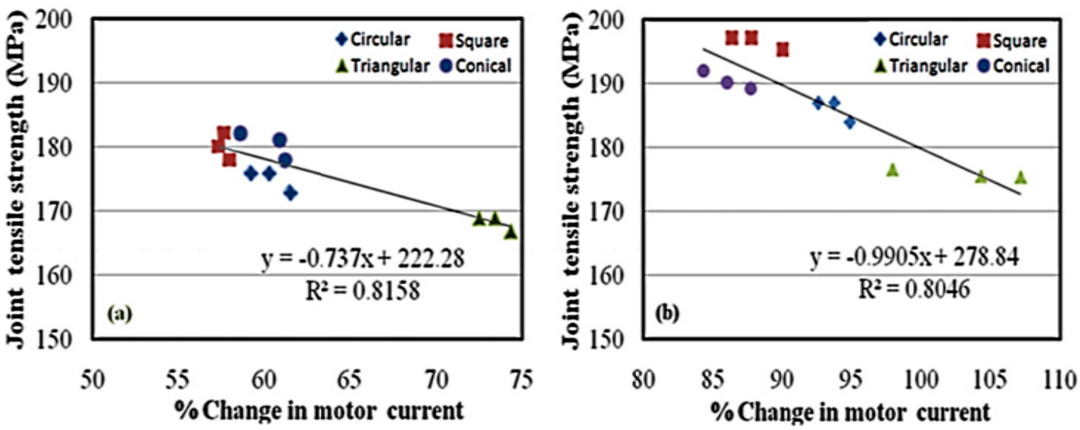


Fig. 10. Correlation analysis between % change in motor current and joint tensile strength; (a) 4 mm thick plates; (b) 6 mm thick plates

A correlation coefficient of 0.8 is obtained between the percentage change in motor current and the joint tensile strength. Hence, percentage change in the line current of main spindle motor of FSW machine tool can be used as a parameter for online monitoring of joint tensile strength of the friction stir welded components.

4. Conclusions

In the present work, an experimental investigation is carried out to explore the feasibility of using spindle motor electrical current as a parameter for monitoring friction stir welding process. Experiments were carried out on aluminium alloy plates using FSW tools with different pin profiles. The acquired electrical current flow to the main spindle motor of FSW machine tool and the tensile strength of the welded joints were studied and a linear regression analysis was carried out. The following inferences were obtained from this experimental investigation:

- The FSW tool pin profiles and work material thickness have significant effect on electrical current and power consumed by the main spindle motor of FSW machine tool. The power consumption of main spindle motor increases with increase in thickness of the materials to be joined and it varies with different pin profiles.
- The friction stir welding of 4 mm and 6 mm thick aluminium alloy plates has shown significant correlation between joint strength and spindle motor current.
- A decreasing trend is observed in joint tensile strength of the work material with respect to the change in line current, due to the variations in tool profiles.
- The square and conical tool pin profiles are found to provide a lesser power consumption with good tensile strength of friction stir welded plates. These tool profiles have a significant role in energy efficient friction stir welding process.

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