PARAMETER OPTIMIZATION AND TEMPERATURE PREDICTION OF FRICTION STIR WELDING FOR ALUMINUM ALLOY; EXPERIMENT, SIMULATION

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ABSTRACT

One of the most efficient methods for joining of aluminum alloys is friction stir welding (FSW) process. In FSW, welding parameters and tool geometry affect the weld strength. Heat is generated by friction between the tool and the workpiece, is important to predict and identify the mechanical and micro-structural changes. In this study, first using the Taguchi approach a design of experiment technique to set the optimal process parameters is investigated. It is shown that with increasing the shoulder diameter, the tensile strength increases and with increasing the tool rotational speed the tensile strength decreases. The traverse speed has less effect. Moreover temperature distribution is investigated experimentally. Results are compared with the software based on finite element method, analytical method, and analytical-empirical method. The capabilities, weaknesses, and accuracy of each method are discussed and suggestion is given.

KEYWORDS: *Aluminum alloy; Friction stir welding; Design of experiment; Taguchi method; Temperature profile.*

1.0 INTRODUCTION

Friction stir welding (FSW) is a solid-state joining process. It is of numerous advantages, including high mechanical properties, low residual stresses, small distortions, no fusion welding defects, no consuming material (Salem, Reynolds & Lyons, 2002). In FSW process, a rotating tool, which has a shoulder and a pin, moves along the welding line. This rotary motion of the tool generates frictional heat, leading to a softened region around the pin. In fact, a weld joint is produced by the extrusion of material from the advance side to the retreating side of the tool (Nicholas & Thomas, 1998). The process has been also applied for extremely curved surfaces (Zaeh & Voellner, 2010). It has been initially developed for Al-alloys but has a great potential for the welding of copper, steels, titanium alloys, metal matrix composites, and different material combinations (Colligan, 1999, Murr, Liu & McClure, 1997).

FSW joints can be enhanced by reducing the heat input, e.g. reducing shoulder diameter, decreasing the rotation rate, increasing traverse speed and additional rapid cooling, but it is difficult for the machine to run regularly in case of low rotary or high traverse speed (Liu, Shen, Huang, Kuang, & Sci, 2009, Shen, Liu, & Cui, 2010). It is

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expected that in FSW joint, weld strength nearly equal to that of the base material to be achieved, if the heat input reduces to a very low level to avoid the softening effect. The main process parameters affecting material flow and weld quality are tool geometry, tool rotation speed, tool traverse speed, vertical pressure and tilt angle of the tool (Cam, 2011). In order to investigate the efficiency of FSW process parameters on this material, most researchers follow the conventional experimental procedures, i.e. varying one parameter at a time while keeping the other parameters constant. However, Taguchi's method is one of the techniques that could be applied to optimize the welding parameters. This method is simple and robust technique for optimizing the welding parameters and widely used to optimize process parameter values in order to improve the quality properties of a product. Further provides advantages over the conventional experimental design methods i.e. it economically reduces the variability of the response variable, indicates the best way for the optimum process conditions during experimental studies (Tutar, Aydin, Yuce, Yavuz, & Bayram, 2014, Bayazid, Farhangi, & Ghahramani, 2015).

In FSW process, a rotating tool having a shoulder moves along the welding line. This rotary motion of the tool generates frictional heat leading to a softened region around the pin and pin stirs material while the shoulder prevents deforming material from being expelled. In fact, a weld joint is produced by the extrusion of material from the advance side to the retreating side of the tool. The friction between tool and workpiece and the deformation made by pin mainly generates the heat flux in the process. The amount of the heat absorbed by tool is little and can be neglected. However, the amount of the heat conducted into workpiece dictates the quality and shape of the weld, as well as the residual stress and the distortion of the workpiece. Consequently, good understanding of the heat transfer process in the workpiece is important to determining welding characteristics.

Nevertheless, the amount of the heat conducted into workpiece dictates the quality and shape of the weld, as well as the residual stress and the distortion of the workpiece. It was noted that temperature must be kept at the optimum level. In case the temperature exceeds the optimum level, heat affected zone (HAZ) softening, distortion and other problems arise. Conversely, if the temperature becomes lower than the optimum level, defects appear (Xu, Deng, Reynolds, & Seidel, 2001). Consequently, a good understanding of the heat transfer process in welding is important for knowing the mechanical and microstructures changes occurring after welding. Many researchers preformed experimental and modelling of the FSW process. To discuss few e.g. a steady boundary value problem (BVP) was developed for AA2195 for the workpiece and experimental tests were preformed to verify the numerical analyses (Chao, Qi, & Tang, 2003). Three-dimensional heat transfer model was investigated by introducing some assumptions to reduce the difficulty of modelling the moving tool and the numerical result was compared with the experimental tests (Song, & Kovacevic, 2003). The thermal histories and temperature distribution during FSW of butt joining the Al6061-T6 plates was studied experimentally using regression analyses and the least squares method predicts the temperatures at the joint line (Hwang, Kang, Chiou & Hsu, 2008).

The amount and intensity of heat generation with parameters that influence heat generation during FSW was investigated too (Mijajlović, Pavlović, Jovanović, Jovanović, & Milćić, 2012). Experimental and numerical analysis of the change of temperature and force in the vertical direction during the friction stir welding of high-strength aluminum alloy 2024 T3 was studied using 3D model by software package

ABAQUS (Veljić, Sedmak, Rakin, Bajić, Meddj, Bajić, Vencislav, & Grabulov, 2014). Since, most of studies do not suggest any simplified recommendation for optimization of parametrs and prediction for temperature distribution. Howerver in this study, a simplified parameter optimization method and a suggestion for temperature prediction are given. First, four parameters are investigated which consider tool rotation speed, tool traverse speed and tool geometry parameters including pin diameter, and shoulder diameter on welding of 5086 aluminum alloy plates and its strength. Then temperature profile is investigated through three approaches, finite element, experimental and analytical. Accuracy of solutions, for fusion welding, is controlled for friction stir welding.

2.0 TENSILE STRENGTH STUDY

Tensile stress study is conducted using the Taguchi approach, design of experiment (DOE) technique, to find the optimal process parameters, then the experiment was preformed and discussed.

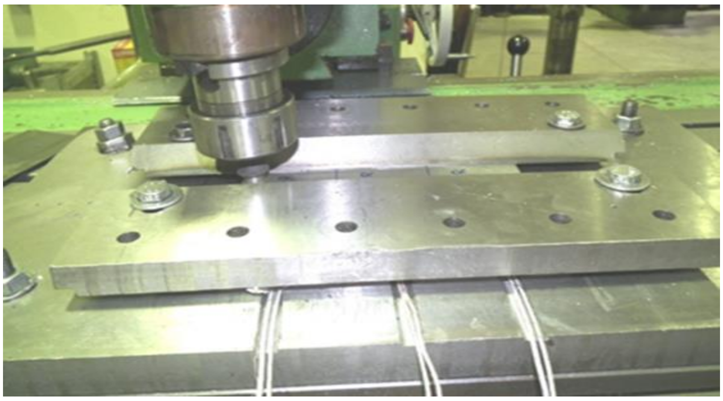
2.1 Experimental Procedure

The experimental studies were performed on 8×100×200 mm plates of 5086 aluminum alloy. Chemical composition of this alloy is shown in the Table 1 and the tensile strength of 334 MPa achieved from the tensile tests.

Table 1. Composition of Aluminum 5086 (wt. %) (ASM Handbook 1990)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.4	0.5	0.1	0.2	3.5	0.05	0.25	0.15

The aluminum plates were seated on a backing plate to avoid separation during the process. The welding has been performed using an FSW adapted FP4M milling machine as shown in Figure 1a. Figure 1.b shows tapered pin with threads. The tool with geometric parameters was made from H13 alloy steel heat-treated to a hardness of 55 HRC. Four process parameters were considered as tool rotational, traverse speed and tool geometries, which include pin base diameter and shoulder diameter in two levels, and illustrated in Table 2. The concavity of tool and tilt angel assumed 3° and 2.5°, respectively.



(a)

(b)

Figure 1. (a) FSW process of aluminum plates (b) tapered pin with threads

Table 2. Parameters and their levels

Shoulder diameter (mm)	Pin diameter (mm)	Tool rotational speed (rev/min)	Traverse speed (mm/min)
20	6	400	12
24	8	800	100

Experiments were carried out according to the principles of DOE in order to determine the effects of the main process parameters. L8 orthogonal array was chosen and applied for this study. The experimental layout for the assumed parameters using the L8 orthogonal array is shown in Table 3.

Table 3. Experimental layout using an L8 orthogonal array

	parameters			
N	Shoulder diameter (mm)	Pin diameter (mm)	Rotational speed (rev/min)	Traverse speed (mm/min)
1	20	6	400	12
2	20	6	800	100
3	20	8	400	100
4	20	8	800	12

5	24	6	400	100
6	24	6	800	12
7	24	8	400	12
8	24	8	800	100

Prior to welding process, surface of plate had been removed from oxide with abrasive paper and cleaned with acetone. The pin plunged into the aluminum plates at the joint line up and the shoulder penetrated plates 0.2 mm.

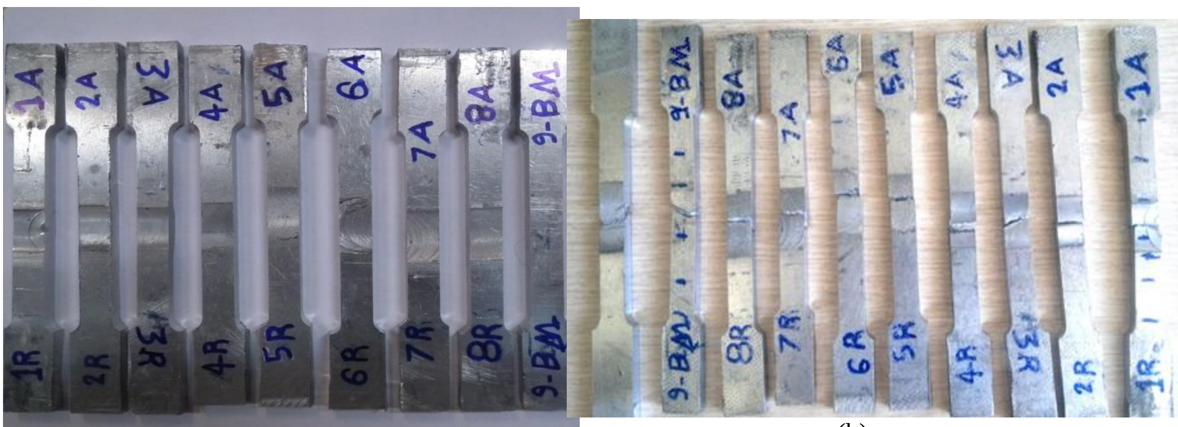
2.2 Tensile Test Results And Discussions

Tensile tests were performed to evaluate the mechanical properties of joints, attained by using different set of parameters. The tensile specimens were produced from weld metal according to ASTME8-B557. The tensile tests were carried out at room temperature by using a universal tensile test model ZWICK with initial strain rate of 10^{-3} /s. The tensile strength was assumed as main characteristic the quality of joint. Figure 2 shows tensile samples before and after the tensile tests and the results of these tests are shown in Table 4.

Table 4. Tensile strength welded samples

Sample	1	2	3	4	5	6	7	8
Tensile strength (MPa)	175.1	141.7	203.6	121.9	157.8	207	191	190

Good relative effects of the different parameters on the tensile test can be acquired by the analysis of variance (ANOVA). ANOVA indicates which process parameters highly affect the quality feature of welds statistically (Esme, 2009, Bozkurt, 2011). Table 5 shows the results of ANOVA analyses for the tensile strength. It is seen the most important factors are the shoulder diameter with contribution of 20.7% and its interference with tool rotational speed and the tool traverse speed of 51.38% and 18.65%, respectively.



(a) (b)

Figure 2. Tensile sample test (a) before (b) after

Table 5. Results of ANOVA for tensile strength

Symbol	Source	Degree freedom	Sum square	Mean square	F-value	P-value	Contribution (%)
A	Diameter	1	1339.9	1339.9	32.02	0.03	20.70
D	Tool rotational speed	1	561.5	561.5	13.42	0.067	8.66
E	A*D	1	3331.9	3331.9	79.62	0.012	51.38
F	Traverse speed	1	0.4	0.4	0.01	0.928	0.01
G	A*F	1	1209.7	1209.7	28.91	0.033	18.65
Error		2	83.7	41.8			0.60
Total		7	6527.2	6485.2			100

Figure 3 illustrates ANOVA analysis, which is related to the effects of the tool rotational speed and the shoulder diameter on the ultimate tensile strength. It can be seen that with increasing the shoulder diameter, the tensile strength increases and with increasing the tool rotational speed the tensile strength decreases. The traverse speed has less affect than tool rotational speed and the shoulder diameter on the ultimate tensile strength. As the results of the interaction, the trend of the tool rotational speed and shoulder diameter remains constant. In other words with increasing the shoulder diameter, the tensile strength increases and with increasing the tool rotational speed the tensile strength decreases. No interaction effect was noticed between transverse speed and shoulder diameter and between tool rotational speed and shoulder diameter. According to ANOVA analysis, the main parameters effects, the optimum condition is shown in Table 6. To verify the improvement proposed by the analyses, a test was performed, in which the tensile strength of this welded specimen was found to be 267.9 MPa, which is in line with the best-estimated condition. The best and defect joint was noticed in lower level rotation speed and pin diameter and upper level of shoulder diameter.

Table 6. Parameters and their levels

Shoulder diameter (mm)	24
Pin diameter (mm)	6
Rotational speed (rev/min)	400
Traverse speed (mm/min)	12

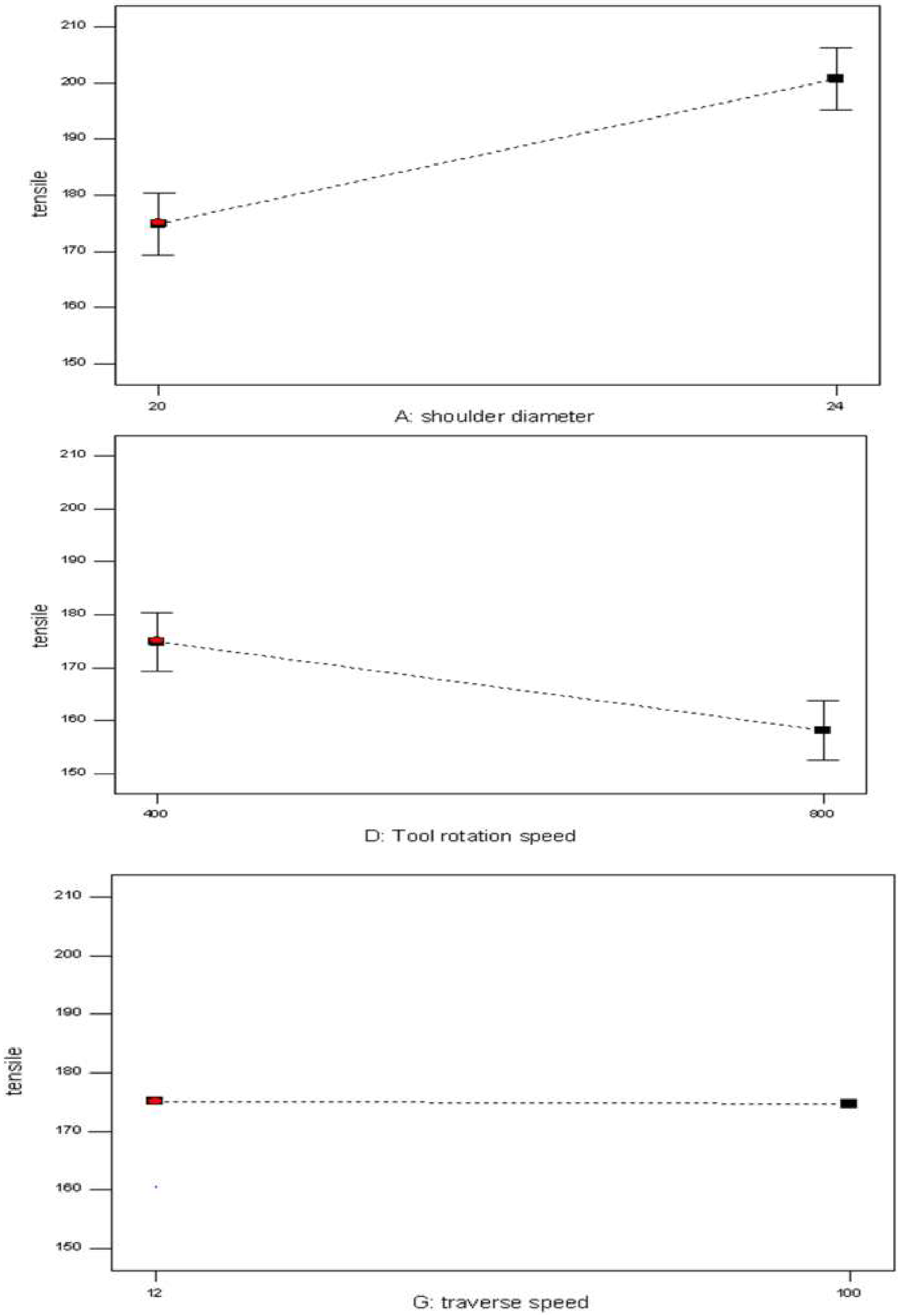


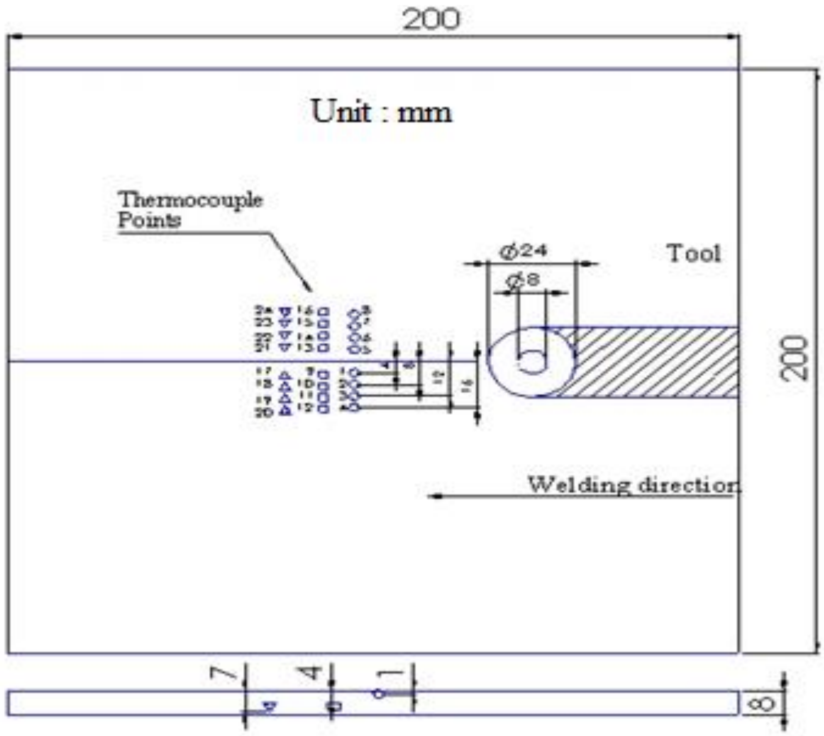
Figure 3. Effects of parameters on tensile strength; (A) shoulder diameter. (D) Tool rotational speed (G) traverse speed

3.0 HEAT TRANSFER STUDY

Temperature distribution is investigated experimentally and then compared with the software based on finite element method, analytical method, and analytical-empirical method.

3.1 Experimental Procedure

Friction stir welding experiment was carried out on Aluminum alloy plates type AL5086-H116 with dimensions of L×W×H=200×100×8 mm. Thermal properties are; K= 25 W/m ºC, ρ= 7800 kg/m^3, C=480 kg/J ºC and temperature at 20ºC (ASM Handbook, 1990). Ahead of measuring the temperature, different welding parameters were tested to ensure free defect condition. One can achieve free defect weld by implementing 400 rpm tool rotational speed and 12 mm/min linear welding speed. The shoulder diameter 24 mm and pin diameter of 6 mm. Thermal properties of H13 alloy steel are; K = 127 W/m ºC, ρ= 2675 kg/m^3, C=900 kg/J ºC and temperature at 20ºC (ASM Handbook, 1990). The plates placed on the backing plate to avoid separation during the FSW process. Temperatures were recorded at twenty-four locations during the process using K-type thermocouples with resolution of 0.1ºC, range of -199.9 to 999.9ºC and an accuracy of ± (0.5% + 1ºC) with a thermometer type TM-946. Recording the temperature during the welding was done by Lutron 801 software and the time step set to 1 second. Mean ambient temperature during the experiments was 23ºC. Layout of locations of thermocouples is depicted in Figure 4. Three rows of thermocouples were placed roughly in the center of the plate along the welding direction. Thermocouples in each row were placed at a certain depth in the plate; the top row is 1 mm and the middle row is 4 mm from the top surface, respectively, and the bottom row is 1 mm from the back surface of the plate. Each row had four thermocouples, which were located at 4 mm, 8 mm, 12 mm and 16 mm from the centerline of the weld. These four locations correspond to the edge of the tool pin, the edge of the tool shoulder and a faraway point from the tool. Holes were pre-drilled from the bottom surface of the plate with 1.5 mm in diameter. Thermocouples were beaded at the tip and glued by OMEGABOND. Figure 5 shows the obtained temperature profiles at some of the locations in the advancing and retreating sides of welding plate.



(a)

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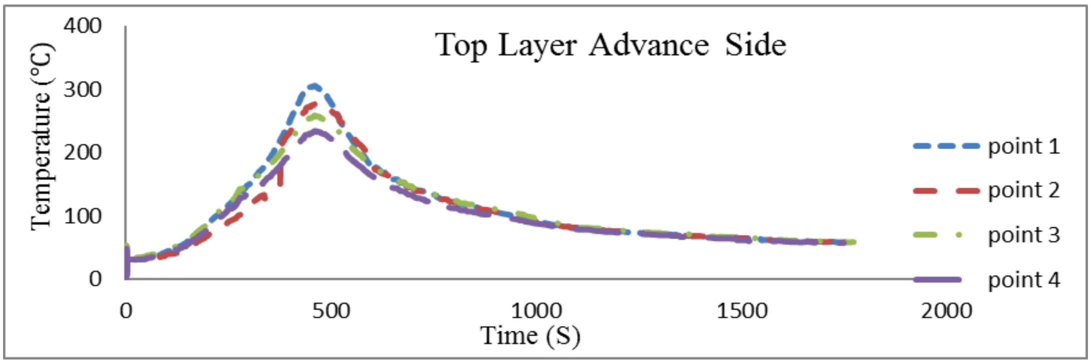
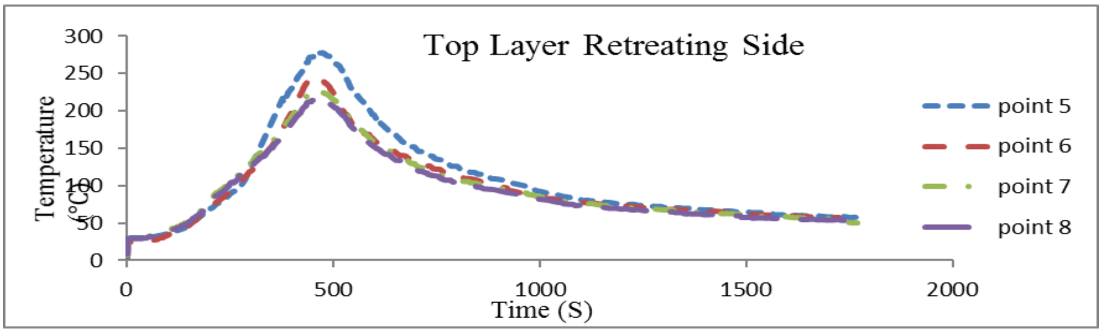
Figure 4. (a) Work piece dimensions (mm) and locations of thermocouples, (b) Picture of setup



(a)



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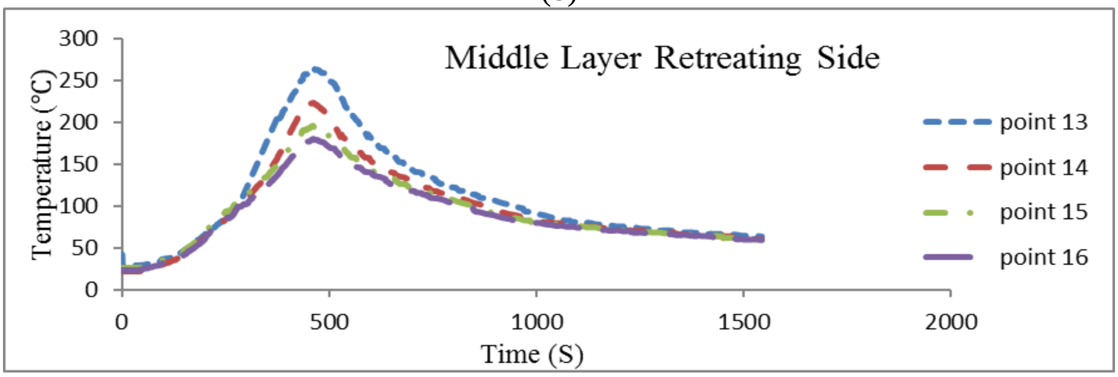

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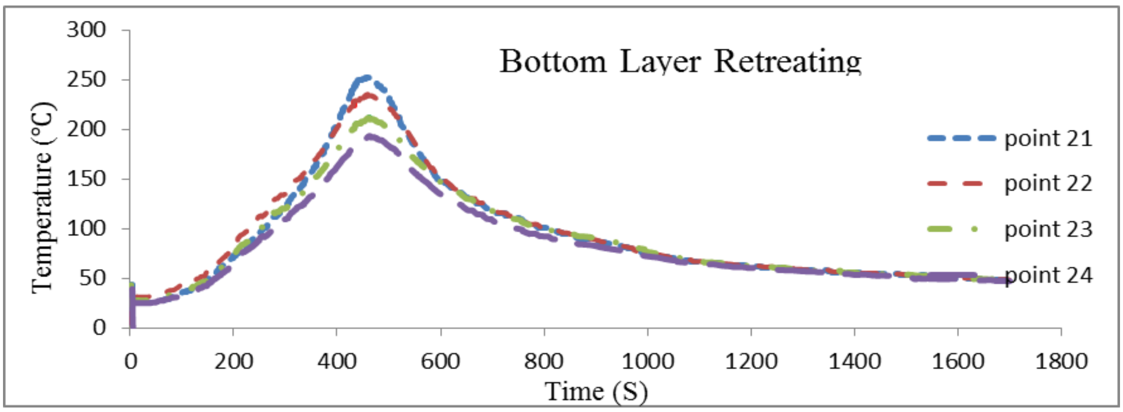

(d)

Figure 5. Experimental temperature profile

3.2 Temperature Results, Modeling And Discussions

The experimental study on temperature profile was accompanied with analytical, analytical-empirical, numerical modeling. Finite element method ABAQUS software (FEM) was used for numerical modeling. In ABAQUS software, the user subroutine DFLUX was used for simulating 3D model of moving heat source with distributed heat flux. Following expression was used to quantify the heat flux generation from the friction between the shoulder and surfaces of the workpiece (Song & Kovacevic, 2003)

$$\bar{q}_s = \mu p \omega r_2 \tag{3}$$

Where $\bar{q}_s$ is average rate of heat source per unit area ($W{\cdot}m^{-2}$), $\omega$is the rotational speed (rad.s^{-1}), $\mu = 0.3$ is the friction coefficient, $p$is the pressure (Pa) applied to the welding tool and r_2 shoulder radius. Following expression was used to quantify the distribution of heat flux (Kejing, 2009):

$$\bar{\bar{q}}(x) = \bar{q}_s\left(\frac{1}{2}\sqrt{1-X^2} + \frac{X^2}{4}\log\frac{1+\sqrt{1-X^2}}{1-\sqrt{1-X^2}}\right)\ ;\ \left(X = \frac{x}{r_2}, |X| \le 1\right) \tag{4}$$

Here X is the distance from tool axis in x direction. Flux generation Equation (3) was inserted for the heat input into Eqution (4). Parameters for numerical simulation and analytical solution are shown in Table 7. Properties, which are obtained from reference (Chao, Qi, & Tang, 2003) and for upper and lower surface of plate, the convective heat transfer coefficients are assumed 30 and 10 $W/m^2.^oC$, respectively.

Table 7. Parameters for simulation and analytical solution

shoulder diameter (mm)	24
applied force (*KN*)	22.4
tool rotational speed (*rpm*)	400
welding speed (*mm/min*)	12
work piece dimension (*mm*)	8x100x200
backup platform (*mm*)	40x300x300
up platform (*mm*)	15x150x250

In these models, the friction between the welding tool and the specimen is replaced by a distributed heat source. Temperature dependent thermal material properties for the workpiece are used in the modeling. In order to obtain a more accurate result, non-uniform mesh size is implemented near weld line for workpiece and tool. Analytical methods based on Equation (5) (Djarot, Darmadi, & Tieu, 2011) and analytical-empirical method based on Equation (6) (Rosenthal, 1946) were used for comparing the temperature profile.

$$T - T_0 = \frac{qv}{\left(8k\alpha\pi^{\frac{3}{2}}\right)} exp(-\xi V) \int_{\omega=0}^{\frac{\tau v^2}{4\alpha}} I_0\left(\frac{r_0 V^2}{2\omega}\sqrt{\left(\xi + \frac{2\omega}{V}\right)^2 + y^2}\right) exp\left[-\left(\omega \frac{u^2}{4\omega}\right)\right] . \frac{d\omega}{\omega^{\frac{3}{2}}} \quad (5)$$

with

$$v\tau = \frac{2\omega}{V}, V = \frac{V}{2\alpha}, \omega = \frac{\tau v^2}{4\alpha}, R_h^2 = \xi^2 + y^2 + z^2 + r^2, u = VR_h$$

and

$$\frac{2\pi(T - T_0)K.H}{q} = exp\left[\frac{v.\xi}{2\alpha}\right] k_0\left(\frac{v.R}{2\alpha}\right) \quad (6)$$

where, T temperature (K),T_0 workpiece temperature before welding (at room temperature, K), *K* thermal conductivity (W/m.K), *q* rate of heat transferred from the source to work piece (W), *v* traveling speed (welding speed m/s), ξ moving coordinate abscissa parallel to x axis, y axis coordinate, α thermal diffusivity ($\alpha = \frac{k}{\rho c}$), ρ density ($\frac{kg}{m^3}$), c specific heat ($\frac{J}{kg.K}$), $R = \sqrt{x^2 + y^2}$ radical expression , H thickness of the work piece (m), r_o point source radius, τ time K_o and I_o Bessel functions.

Figure 6 compares the results of FEM simulation, analytical, analytical-empirical 2D Rosenthal’s equation with the obtained experimental data. It is seen Rosenthal’s solution and finite element simulation by ABAQUS are much closer to the experimental data. Hence, 2D Rosenthal’s equation still is a good approximation for this process.

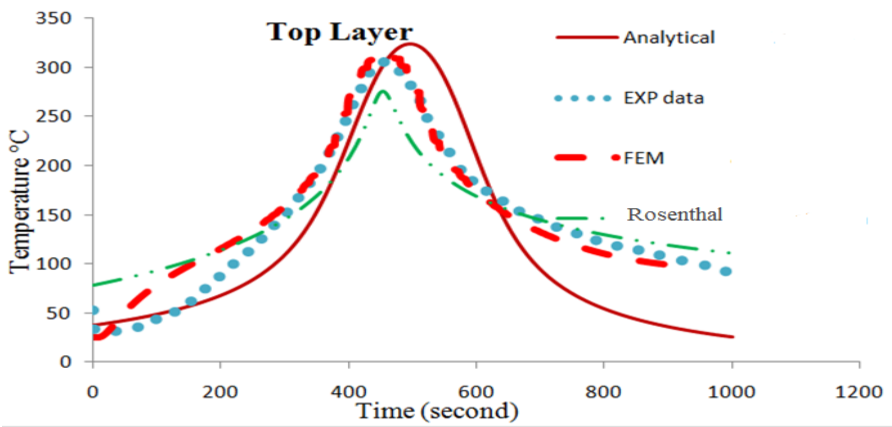

Figure 6. Comparison of temperature for point 1: Experiment, Finite Element Method simulation, Analytical (Djarot, Darmadi, & Tieu, 2011) and Rosenthal (Rosenthal, 1946)

4.0 CONCLUSIONS

Friction stir welding on 5086-H116 aluminum alloy plate was studied by using the Taguchi method for optimization of parameters. The process parameters were optimized with respect to the tensile strength of the joint. Experiment was carried out for temperature prediction and compared with analytical, analytical-empirical, and finite element method. Following conclusions can be drawn based on the experimental and analytic results.

- The best and defect-free FSW in 5086-H116 aluminum alloy plate's joints was achieved in lower level rotation speed and pin diameter and upper level of shoulder diameter.
- The interaction of shoulder diameter with tool rotation speed plays an important role with contribution of 51.38% and 18.65%, respectively.
- Increasing the shoulder diameter, the tensile strength increased and with increasing the tool rotational speed the tensile strength decreased. The traverse speed had less effect.
- Temperature distribution is achieved experimentally. Results were compared with the software based on finite element method (FEM), analytical, and analytical-empirical. The analytical-empirical Rosenthal's model indicated good agreement with the experimental data.

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