International Journal of Engineering and Technology Innovation, vol. 8 no. 1, 2018, pp. 64 - 75

Effect on Tool Design and Heat Input of Some Welding Parameters in Friction Stir Welded Interstitial Free Steels

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Received 04 February 2017; received in revised form 25 April 2017; accepted 04 May 2017

Abstract

The friction stir welding process (FSW), a new solid state welding, are widely used in automobile and aerospace industries as compared to conventional fusion welding. The tool speed (rotational and translational), traverse speed, shoulder diameter and pin diameter are mainly responsible for the heat generation in FSW which are required to be optimized. The contribution of rotational tool speed is approximately three times higher than that of translational tool speed. This paper presents derivation for maximum heat generation to obtain best optimum tool geometry (tapered or cylindrical) in FSW through mathematical model using various parameters and necessary constraints. Two models namely genetic algorithm and regression model of response have been developed to compute optimum welding parameters. The genetic algorithm optimization technique has been employed for tapered and cylindrical FSW tool whereas the regression model has been employed for cylindrical FSW tool to obtain optimum tool geometry at constant welding speed. It has been found from genetic algorithm using MATLAB and regression modelling using MINITAB-17 that the optimum parameters for effective tool design are shoulder diameter as 12 mm, pin diameter as 4 mm and tool rotation speed as 250 rpm.

Keywords: friction stir welding, FSW, tool geometry, genetic algorithms, and regression modelling

1. Introduction

Steel has become an integral part of life and widely used in almost all industries and automobiles industries in particular due to surface quality, gauge tolerance, uniform mechanical properties, etc. The low carbon (< 0.003% C) and nitrogen (0.004% N) contents in interstitial free steel make it highly formable which confer low yield strengths and high resistance to thinning [1].

Due to the extensive research on friction stir welding (FSW) during the last decade and its promising feature, there has been a growing interest in the use of this technology. FSW derived from conventional friction welding has an advantage of solid state welding viable for joining aluminum alloys, copper, magnesium and other low-melting point metallic materials. Investigations have been being carried out on FSW technique applicability on harder materials like steel and titanium. In FSW process, high quality weld can be fabricated even in absence of solidification, cracking, oxidation, porosity and other defects normally found in traditional fusion welding [2].

In FSW, a specially designed rotating tool (Tapered/cylindrical), consisting of a pin and a shoulder, is plunged through the material. The tool is then traversed in the desired directions as the contact of the rotating shoulder increases the

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temperature of the modified surface, the temperature however remaining below the melting point of the base material. The heat generation in FSW developed due to friction as well as deformation while heat is generated conventional welding technique due to friction only in which one part of mechanical energy is transferred to tool, consumed in welding while other part used in deformation process and rest of the energy transformed into heat [3-4].

Tool geometry is the most significant parameter which influences material flow and heat generation, and in turns the quality of weld joint. In the present work, various pin profiles such as cylindrical and tapered cylindrical have been developed using analytical model for heat generation. Taper cylindrical tool provides mechanical properties over cylindrical pin profile [5-9]. Considering rotating tool as the main element consisting of a shoulder and a pin that move along the butting surfaces of two rigidly clamped workpiece on a backing plate to produce heat is facilitated by friction [10]. Study on influence of pin geometry on mechanical properties in 2014-Aluminium alloy has been carried out. Taper screw thread pin weld has higher weld joint efficiency (75%) to that of threaded cylindrical tool pin profile welds [11]. Other parameters, which influence the quality of weld joints are rotational speed of tool, welding speed, normal force and tool geometry [12]. Tool pin profile affects the tensile strength of friction stir weld [13]. There are different types of pin profiles such as cylindrical, truncated cylindrical, threaded cylindrical, triangular and square pins profile to fabricate the joints and studied the effect of tool design and welding parameters on defect formation. The results obtained by square pin profile were found to be effective on microstructure and mechanical properties of aluminum joints [14, 15]. Its calculation for torque/power from experiments in the expression for heat source and also introduced a torque based heat input model for SC profile [16]. Furthermore, Schmidt et al. and Ulysse developed an analytical tool for heat generation for straight cylinder having concave shoulder based on various assumption in which heat is generated on shoulder tip and neglected on the probe and also found 80-90% of the mechanical power transferred to the welding tool transform into heat [17-18].

2. Mathematical Modelling

The frictional heat developed between the tool and the work piece due to relative motion can be obtained with the help analytical expressions which accounts for geometrical shape of the tool, shoulder diameter, the pin surface and pin tip surface. There are mainly two contributors/contributions to the heat generation:

(1) Frictional dissipation.

(2) Plastic dissipation.

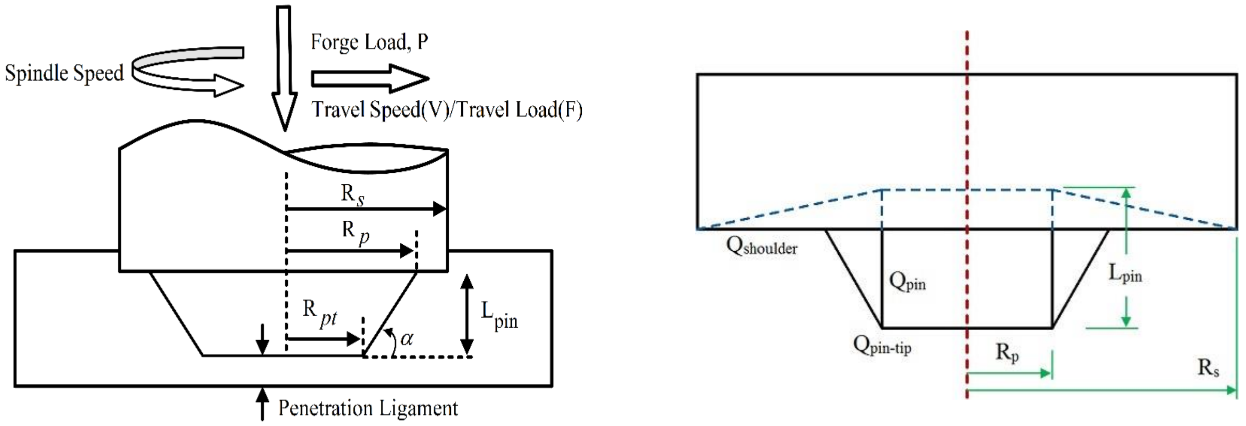
2.1. Heat generation equation for taper cylindrical pin profile

In the present model, the purpose is to combine the different features of models presented by Schmidt et al. and Shercliff et al. [17, 19] to apply in the FSW process. A small shoulder and larger tapered pin is preferred due to the heat generated at the shoulder is able to flow at the root of joint and allow stirring in tungsten carbide. The energy transferred by the tool into work piece via friction is only being considered in this model. Here, we also define the optimized dimension of tapered cylindrical tool i.e., shoulder radius, pin radius, pin tip radius, tool length, cone angle and shoulder surface angle. The following underlying assumptions were made for the mathematical modelling.

(1) The mathematical estimation based on a general assumption of uniform contact shear stress τ contact was considered.

(2) The sliding condition the shearing takes place at the contact interface.

(3) Due to friction interface conditions, the frictional shear stress τ friction was considered. The shear stress estimated for a sliding condition was $\tau_{contact} = \tau_{friction} = \mu p = \mu\sigma$.



(a) Typical tool geometry having tapered tool profile along with related parameters of heat generation in FSW

(b) Typical tool profile (cylindrical) along with related parameters of heat generation in FSW

Fig. 1 Typical tool along with related parameters of heat generation in FSW

The total heat generated with a tapered FSW tool. The expression for the heat generation by rotation and translation of the friction stir welding tool shoulder are defined in Eqs. (1) and (2), respectively.

$$Q_{shoulder,rotation} = \int_0^{2\pi}\int_{R_p}^{R_s} \omega r^2 k\tau dr d\theta = 2\pi\omega k\tau\left(\frac{R_s^3 - R_p^3}{3}\right) \tag{1}$$

$$Q_{shoulder,translation} = \int_0^{\pi}\int_{R_p}^{R_s} v\sin\theta k\tau r dr d\theta = vk\tau(R_s^2 - R_p^2) \tag{2}$$

The heat generation by the rotation of the pin surface is given by Eq. (3).

$$Q_{pin,rotation} = \int_0^{2\pi}\int_0^{L_p} \omega k\tau r^2 dz d\theta = 2\pi\omega k\tau\left(R_{pt}^2 L + R_{pt} L_p^2 \tan\alpha + \frac{L_p^3}{3}\tan^2\alpha\right) \tag{3}$$

The expression for the heat generated by rotation and translation of the FSW tool pin tip are define in Eqs. (4) and (5) respectively.

$$Q_{pin-tip,rotation} = \int_0^{2\pi}\int_0^{R_{pt}} \omega r^2 k\tau dr d\theta = 2\pi\omega k\tau\left(\frac{R_{pt}^3}{3}\right) \tag{4}$$

$$Q_{pin-tip,translation} = \int_0^{\pi}\int_0^{R_{pt}} v\sin\theta k\tau r dr d\theta = vk\tau R_{pt}^2 \tag{5}$$

The frictional heat generation by the translation of the pin through the work piece material was estimated by the evaluating the normal and shear forces acting on the front face, or leading half, of the pin equation define in Eq. (8).

$$Q_{normal} = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_0^{L_P} v\cos\theta\sigma k r dz d\theta = vk\sigma(2R_{pt}L_p + L_p^2\tan\alpha) \tag{6}$$

$$Q_{shear} = \int_0^{\pi}\int_0^{L_p} v\sin\theta\tau k r dz d\theta = vk\tau(2R_{pt}L_p + L_p^2\tan\alpha) \tag{7}$$

$$Q_{pin,translation} = Q_{shear} + Q_{normal} = vk(\sigma+\tau)(R_p L_p + L_p^2\tan\alpha) \tag{8}$$

By combining all the Eqs. (1) to (8), the total heat generated by rotation and translation of the FSW tool can be obtained and is given in equation.

$$\text{Total heat generated } (Q) = \begin{bmatrix} Q_{shoulder,rotation} + Q_{shoulder,translation} + Q_{pin,rotation} + Q_{pin-tip,rotation} \\ + Q_{pin-tip,translation} + Q_{normal} + Q_{shear} \end{bmatrix}$$

$$\text{Total heat generation } (Q) = \left[\begin{array}{l} 2\pi\omega k\tau(R_s^3 - R_p^3/3) + vk\tau(R_s^2 - R_p^2) + \\ 2\pi\omega k\tau(R_{pt}^2 L_p + R_{pt} L_p^2 \tan\alpha + \tan^2\alpha \dfrac{L_p^3}{3}) \\ +2\pi\omega k\tau(\dfrac{R_{pt}^3}{3}) + vk\tau R_{pt}^2 + v\sigma k(2R_{pt}L_p + L_p^2 \tan\alpha) \\ +vk\tau(2R_{pt}L_p + L_p^2 \tan\alpha) \end{array} \right]$$

$$Q = \left[\begin{array}{l} 2\pi\omega k\tau(\dfrac{R_{pt}^2}{3} + R_{pt}^2 L_p + R_{pt} L_p^2 \tan\alpha + \tan^2\alpha \dfrac{L_p^3}{3}) \\ +v\tau k(2R_{pt}^2 + (1+3^{1/2})(2R_{pt}L_p + L_p^2 \tan\alpha)) \end{array} \right] \tag{9}$$

2.2. *Heat generation equation for cylindrical pin profile*

The general expression for heat generation at each of the different zones of the tool/work-piece interface is,

$$Q_{shoulder} = \frac{2}{3}\pi\omega((1-\delta)\mu P + \delta\tau_{yield})(R_s^3 - R_p^3) \tag{10}$$

$$Q_{pin} = 2\pi\omega((1-\delta)\mu P + \delta\tau_{yield})R_p^2 L_p \tag{11}$$

$$Q_{pin-tip} = \frac{2}{3}\pi\omega((1-\delta)\mu P + \delta\tau_{yield})R_p^3 \tag{12}$$

In the case of a cylindrical pin profile, the heat generation expression simplifies to ($R_{PT} = R_{PS}$). Therefore, the total heat generation from cylindrical FSW tool and work piece interface can be expressed as:

$$Q_{Total} = Q_{shoulder} + Q_{pin} + Q_{pin-tip}$$

$$Q_{Total} = \frac{2}{3}\pi\omega\tau_{contact}(R_s^3 + 3R_{ps}^2 L_p) \tag{13}$$

This correlates with the results found by Khandkar et al. [16] or Schmidt et al. [17].

2.3. *The relationship between welding conditions and heat input*

Welding heat input is one of the most important factors for FSW. The mechanical properties of stir zone (SZ) under as-welded and post-welded heat treatment (PWHT) states vary with different welding heat inputs. The welding heat inputs within SZ are very difficult to be measured due to the intense plastic deformation induced by the rotation and the translation of a stirring tool. In FSW, the friction effect between the tool and the welding workpiece can lead to temperature rises. Based on the heat flow model of HAO et al. [20], the welding heat input can be described as:

$$q = \frac{4}{3}\pi^2 \mu PNR^3 \tag{14}$$

In this, μ is the friction coefficient; P the pressure on the stir zone (N/m^3); N the rotation speed of the tool (s^{-1}) and R the shoulder diameter (m). In Eq. (14), it is assumed that heat is generated solely between the shoulder of the rotating tool and the weld metal. The pressure P on the stir zone is the load per unit area applied by the downward pressure of the shoulder. From Eq. (14), heat quantity q is the proportional to the pressure P and speed of rotation N and in a third-order proportion to the shoulder diameter R. If the welding speed is considered, Eq. (15) is obtained

$$Q = \frac{4}{3}\pi^2 \mu PR^3 \frac{\alpha\omega}{v} \tag{15}$$

In this, Q is the heat input per length, α is the heat input efficiency, and υ is the welding speed. In this work, only one kind of stirring tool is used and the welding condition is the same, α, μ, P and R are assumed to be constant, and only ω and υ are variable, so Q can be expressed as

$$Q = \alpha\beta\frac{\omega}{v} \tag{16}$$

where β is a coefficient. The peak temperature is determined by employing the Arbegast [21] empirical relationship:

$$\frac{T}{T_m} = K(\frac{\omega^2}{2.362v \text{ x } 10^4})^{\gamma} \tag{17}$$

In this, T is the peak temperature of SZ during FSW, T_m is the melting point of the alloy, and K and γ are coefficients. γ is reported to range from 0.04 to 0.06, and K is between 0.65 and 0.75. In this work, K and γ are assumed to be constants because of the same welding condition. The welding heat input is dependent on the rotation speed and welding speed. When the heat input is too large, the crystal increases in size whereas when the heat input is too small, internal defects occur and the strength decreases. Both ω/υ (liner energy, LE) and ω^2/υ (heat index, HI) are used to quantify the heat input in this work. It should be noticed that LE is mainly affected by the welding speed, while HI is affected by the rotation speed.

2.4. The Relationship between torque, power and local heat flux.

Khandkar et al. [16] has proposed an input torque based model for FSW of aluminium alloys. The torque required to rotate a circular shaft relative to the plate surface under the action of an axial load. The Eq. (18) is used to calculate total torque (at all the interfaces) can be expressed as:

$$M_{Total} = \int_{R_p}^{R_s} (\tau r)(2\pi r)\, dr + \int_0^{R_p} (\tau r)(2\pi r)\, dr + (\tau r)2\pi R_p L_p \tag{18}$$

From Eq. (18), it is obvious that the torque depends both on the applied tool rotational speed and tool design (shoulder and pin diameter). The total torque, which is the sum of the three torque components, related to the average power input by

$$P_{avg} = M_{Total}\,\omega \tag{19}$$

where, ω is the tool rotational speed. The moving heat flux was calculated by Eq. (20). The finite element heat flux can be related to the radial position r to give.

$$q^0(r) = \frac{P_{av} r}{(2/3)\pi R_s^3 + 2\pi H_p R_p^2} \tag{20}$$

where, $q^0(r)$ is the local heat flux and is linearly related to r.

3. The Model

IF steels used as a welding sheet in present study are of rectangular shape having dimensions 300 mm length, 50 mm breadth and 1.6 mm thickness. The chemical properties of parent material and the physical properties of work piece material are presented in Table 1 and Table 2, respectively. The FSW tool is made of tungsten carbide, which has excellent toughness and hardness over temperature (minimum of 1200℃). The material is apparently insensitive to sudden change in temperature and load during welding trials. The dimension of various operating parameters for the present study are - tungsten carbide tool shoulder diameter 15 mm, pin (tapered / cylindrical in shape) diameter 6 mm, tool length 60 mm, pin height 1.5 mm and tilted by 3^0 during FSW. The ranges of operating parameters are tool rotation speed from 250 - 700 rpm at constant traverse speed of 120 mm/min and applied normal force of 34.9 kN. Two different tool pin profiles (Tapered and cylindrical) have been used to fabricate the joints. Heat is generated by the stirring tip of the tool on the material being welded and the shoulder provides the additional friction as well as prevents the plasticized material to escape from the weld region. So, both pin and shoulder are important parameter for the quality of weld. A general analysis of variance technique was used for selecting optimum welding parameters such as the tool rotation speed, shoulder diameter and pin diameter as the control factors. Each factor had four levels as given in Table 3. The levels of shoulder diameters are 12, 15, 16 and 18 mm. The pin diameter levels are 4, 5, 5.5 and 6 mm. The tool rotation speed level are 250, 350, 450 and 600 rpm. Each experiment was conducted four times to ascertain the repeatability of the procedure for each of the 16 inputs as indicated in Table 5. To compute the amount of torque, power and local heat flux at the tool- work piece interface, heat transfer model is designed. These data are then further utilized in regression modelling.

Table 1 Chemical composition of the selected IF steel (in wt %)

C	Mn	S	Si	Al	N_2	Ti	P	Fe
0.002	0.079	0.0089	0.006	0.0359	0.003	0.0657	0.0109	Balance

Table 2 Typical mechanical properties of IF steel at room temperature

Material properties	IF Steel	Material properties	IF Steel
Yield stress (N/mm²)	137	Frictional coefficient	0.4
Density (kg/m^3)	7870	Melting temperature (K)	1800
Thermal conductivity (W/m°C)	51.9	Tensile strength (N/mm²)	302
Specific heat (J/kg° C)	461	Range of strain rates (per Second)	0.001 to 750

Table 3 Tool rotation speed, shoulder diameter and pin diameter design matrix

Variables	Level 1	Level 2	Level 3	Level 4
Tool rotation speed (rpm)	250	350	450	600
Shoulder diameter (mm)	12	15	16	18
Pin diameter (mm)	4	5	5.5	6

4. Results and Discussion

The data generated from the present models have been tabulated and analyzed on the underlying principles of Heat transfer and friction. The energy is transferred by the tool into the work piece due to friction only. Various features like heat generation, pin surface, pin tip surface etc. of developed model have been analyzed.

4.1. Heat energy estimation

Table 4 represents value of heat generated during FSW process to demonstrate distribution of heat generated at various surfaces (shoulder and pin). The following can be inferred from Table 4.

(1) For a given transverse speed heat generation increases with increase in tool rotating speed.

(2) Heat generated due to rotational speed is in the range of 73-88%.

(3) Heat generated due to translational speed is in the range of 12-27%.

(4) Heat is generated from shoulder surface of the tool is around 85 % which significantly the heat generation over other contact surface.

The percentage of heat contribution generated due to rotational and translational has been computed using the basic frictional heat generation relation as given above through Eqs. (1)-(9).

Based on tool geometry heat generation, i.e., contributions from the different surfaces compared to the heat generation, tool shoulder about 85% heat generation [22]. Chao et al. [2] have modeled this process and observed that majority of heat generated from friction, about 95% transferred into the work piece and only 5% flows into the tool as well as about 80% of plastic deformation work is dissipated as heat. The heat efficiency in FSW is thus 95%, which is very high relative to the traditional fusion welding where the heat efficiency is typically 60 to 80%.

Table 4 Heat generated during friction stir welding at Various Speed.

Tool Rotation Speed (rpm)	$Q_{shoulder\text{-}rotation}$	$Q_{shoulder\text{-}translation}$	$Q_{pin\text{-}rotation}$	$Q_{pin\text{-}translation}$	$Q_{pin\ tip\text{-}rotation}$	$Q_{pin\ tip\text{-}translation}$	Total heat (watt)
250	684.366	179.398	32.438	63.459	13.8649	15.187	988.7
300	821.228	179.398	38.925	63.459	16.637	15.187	1134.8
350	957.228	179.398	45.372	63.459	19.639	15.187	1280.04
400	1094.98	179.398	51.9	63.459	22.184	15.187	1427.108
450	1231.843	179.398	58.388	63.459	24.956	15.187	1573.23
500	1395.04	179.398	66.123	63.459	28.263	15.187	1747.47
550	1505.594	179.398	71.363	63.459	30.5	15.187	1865.5
600	1642.457	179.398	77.850	63.459	33.275	15.187	2011.63
650	1779.346	179.398	84.339	63.459	36.048	15.187	2157.77
700	1916.21	179.398	90.826	63.459	38.82	15.187	2303.899

4.2. *Effect of tool rotation speed and traverse speed on heat input*

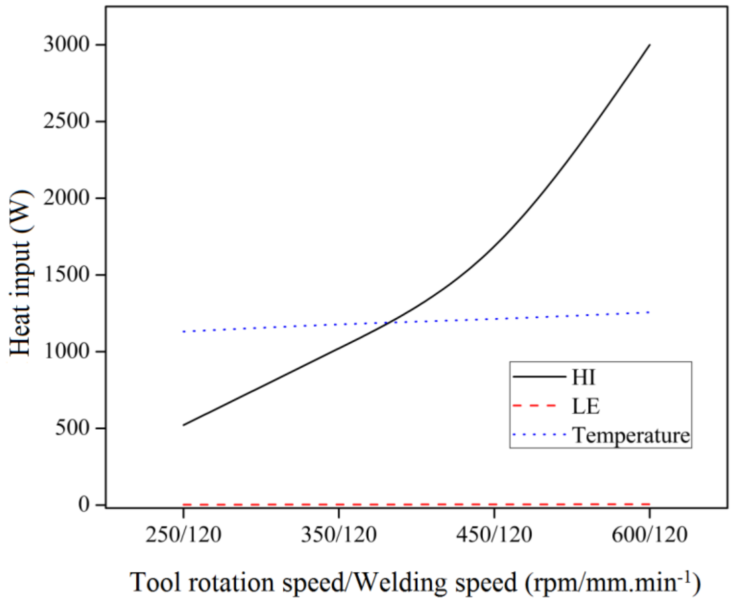


Fig. 2 Variation of heat input with tool rotation speed

The IF steel sheets are joined by FSW using LE and HI as heat input where temperature is related to ω^2/υ ratio. From Fig. 2, it is observed that heat input (developed) is increasing with increase in tool speed ratio (ω^2/υ). For given traverse speed, the temperature increases with increase in rotational speed. The temperatures have been computed using Eq. (17) in order to get optimal welding condition. The optimal welding condition for the present study has been found as heat input (developed) equal to 1.34 kW at 400 rpm, 1.6 kW at 450 rpm and 4.10 kW at 700 rpm. Edwards et al. [23] has reported optimal welding condition as 1.4 kW <heat input > 2.5 kW for high melting materials.

4.3. *Analysis of heat generation for tapered cylindrical and cylindrical tool pin profile*

A simple modification in geometry of a cylindrical pin is a taper pin profile. Heat generated at different surface can be calculated from available numerical equations. Figs. 3 and 4 have been plotted to predict variation in heat generation (developed) with tool rotation speed. In fact, Fig. 3 represents variation in heat generation with tool speed in case of tapered cylindrical pin and Fig. 4 represents variation in heat generation with tool speed in case of cylindrical pin. It can be concluded from Fig. 3 and Fig. 4 that heat generation (developed) increases with increase in tool rotational speed. The tapered tool with the shoulder angle of 3^o has been found to produce a larger deformation region as well as higher mechanical properties compared to the cylindrical tools employed in this study. Biswas et al. [24] Study the ratio of heat generation from plastic deformation to friction dissipation in the conical threaded pin is 44 % more than that of cylindrical pin of similar shoulder diameter. Increase in the value of tool rotating speed (250 to 600 rpm) at constant traverse speed (120 mm/min) increases the amount of heat generation which is generated by the tapered cylindrical FSW tool pin.

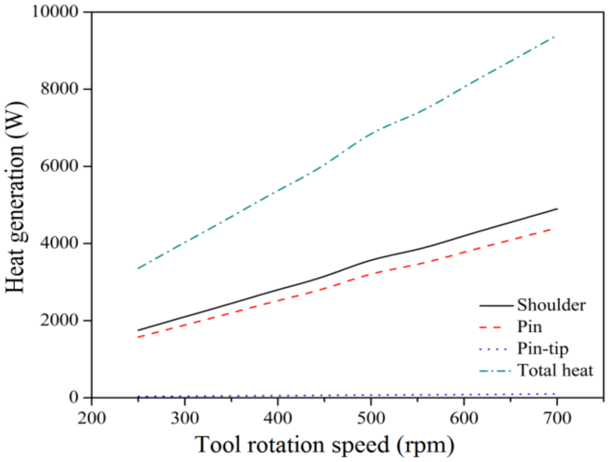


Fig. 3 Variation of heat generation with tool rotation speed for tapered cylindrical pin

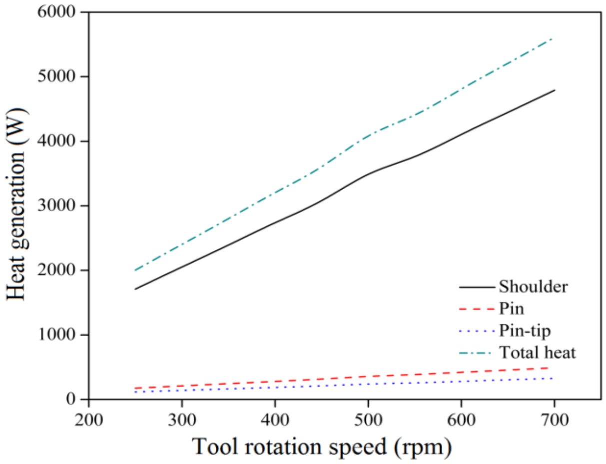


Fig. 4 Variation of heat generation with tool rotation speed for cylindrical pin profile

The MATLAB software was utilized for optimization by Genetic algorithm. Evolutionary algorithms are successfully applied to optimization problems in various fields, especially engineering. Genetic algorithm provides us the flexibility to choose the value of parameters on which its performance depends and hence considered to be the biggest advantage of it. Genetic algorithm gives a solution to the optimization problems inspired by natural evolution such as inheritance, selection, mutation and crossover. Many real time problems can be solved by using genetic algorithm rather than conventional optimization techniques as the genetic algorithms most likely to converge to a solution nearer to optimal region. GA uses a coding of variables instead of variables directly such as population of points instead of a single point and stochastic operators instead of deterministic operators [25, 26]. The same approach can be applied on FSW models using variable parameters like traverse speed, pin dia., shoulder surface angle, cone angle, tool rotation speed and manage to minimize the difference between total heat generation in tapered and cylindrical tool. In the following section, optimization problem will be defined with our objective to optimize the dimensions of tool i.e. shoulder diameter, pin diameter, pin tip diameter, tool shoulder height, shoulder surface angle and cone angle so as to ensure the amount of heat generation using the tapered as well as cylindrical tool pin profile. The design parameters of tool and working conditions are given as input for which equivalent parameters of cylindrical as well as tapered tool are to be found. The parameters that are to be optimized are six variable parameters. The objective function can be chosen as:

$$F(R_S,\ R_p,\ R_{PT},\ \alpha,\ \theta,\ RPM) = (Q_{Tapered} - Q_{Cylindrical})^2 \tag{21}$$

Subject to constrained variables such as:

(1) $12\ \text{mm} \leq RS$ (shoulder diameter) ≤ 18 mm

(2) $4\ \text{mm} \leq RP$ (pin diameter) ≤ 6 mm

(3) $2\ \text{mm} \leq RPT$ (pin-tip diameter) ≤ 3 mm

(4) $1 \leq \alpha$ (cone angle) $\leq 3°$

(5) $10 \leq \theta$ (shoulder surface angle) $\leq 12°$

(6) $250 \leq RPM$ (tool rotation speed) ≤ 600.

All the six variables used for the optimization algorithm is nonlinear function. Optimum parameters such as shoulder dia. 12mm, pin dia. 4mm, cone angle 3^o, shoulder surface angle 10^o and tool rotation speed 250 rpm are obtained for optimization problem using genetic algorithms (GA). Chao et al. [2, 27] have welded steel using parameters as rotational speed of 400 rpm, traverse speed of 120 mm/min, frictional heat source of 1.4 kW and tool dimensions (shoulder dia. 12 mm and pin dia. 4 mm).

4.4. Regression model response

The response based L16 test has been employed using Design of experiment approach to develop process window as shown in Table 5. These results were conducted and three responses such as torque, power and local heat flux were used for the response regression surface modelling using MINITAB 17. Response optimization helps to identify the combination of input variable setting that jointly optimize a single response or a set of response.

Table 5 Responses welded interstitial free steel plates in as-weld condition

Test No.	Parameters			Responses		
	Rotational Speed (rpm)	Shoulder dia. (mm)	Pin dia. (mm)	Torque (kN-mm)	Power (kW)	Local heat flux (W/mm^2)
1	250	18	6.0	127	3	12
2	250	16	5.5	90	2	11
3	250	15	5.0	74	2	10
4	250	12	4.0	39	1	8
5	350	18	5.5	126	5	17
6	350	16	6.0	91	3	16
7	350	15	4.0	73	3	14
8	350	12	5.0	40	1	12
9	450	18	5.0	125	6	22
10	450	16	4.0	88	4	19
11	450	15	6.0	77	4	20
12	450	12	5.5	41	2	16
13	600	18	4.0	124	8	28
14	600	16	5.0	89	6	26
15	600	15	5.5	75	5	26
16	600	12	6.0	42	3	23

DOE Method is very effective to deal with responses influenced by many parameters. It is a simple, efficient and systematic approach to determine optimal process parameters. This method is devised for process optimization and identification of optimum levels of process parameters for given responses.

4.4.1. Regression modelling

A nonlinear regression model has been developed to predict response (T) of FSW IF steel based on analytical approach in order to correlate process parameter and response (T) of welded joints. Regression coefficients are calculated using response surface regression. The response (T) such as torque, power and local heat flux of the joints are functions of tool rotational speed (TRS), shoulder diameter (SD) and pin diameter (PD) and it can be expressed as

$$T = f(TRS, SD, PD) \tag{22}$$

For the above three factors, the developed mathematical model regression equations are given below.

$$Torque\ (kN-mm) = -139.7 - 0.00028TRS + 13.963SD + 1.87PD \tag{23}$$

$$Power\ (W) = -7.383 + 0.008639TRS + 0.5964SD - 0.333PD \tag{24}$$

$$Local\ heat\ flux\ (W/mm^2) = -13.65 + 0.042448TRS + 0.8008SD + 0.285PD \tag{25}$$

The adequacy of the models so developed was tested using the analysis of variance technique. The desired level of confidence was considered to be 95%. The relationship may be obtained and provided that the calculated value of the F and R ratio of the model developed should not exceed the standard tabulated value of F and R ratio for a desired level of confidence. The F test has been carried out to study the significance of the process parameter. The high F value indicates that the factor is highly significant in affecting the response of the process. They are also used to find the contribution of each parameter. Thus, the higher the value of F ratio is the more dominant the welding parameters are. The analysis of variance for torque, power, and local heat flux are shown in Table 6, 7 and 8 respectively. For the models developed, it was seen that the calculated R^2 values and adjusted R^2 values are above 90%. These values indicate that the regression models are quite adequate.

Table 6 Analysis of variance table for torque

Analysis of variance for torque: (Response Surface Regression): R-sq = 98.32%, R-sq(adj) = 97.90%, R-sq(pred) = 96.77%, S = 4.57174					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	14653.0	4884.3	233.69	0.000
Linear	3	14653.0	4884.3	233.69	0.000
Tool rotation speed	1	0.0	0.0	0.0	0.975
Shoulder dia.	1	14622.4	14622.4	699.61	0.000
Pin dia.	1	30.6	30.6	1.46	0.250
Residual Error	12	250.8	20.9		
Total	15	14903.8			

In addition, the F-test named after fisher has also a significant effect on the torque as the process parameter. Usually, the process parameters have a significant effect on the quality characteristics when F is large. The result indicates that the considered process parameters are highly significant factors affecting the torque of FSW joints in the order of tool rotation speed, shoulder diameter and pin diameter.

Table 7 Analysis of variance table for power

Analysis of variance for power: (Response Surface Regression): S = 0.367969, R-sq = 96.70%, R-sq(adj) = 95.88%, R-sq(pred) = 92.81%.					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	47.6152	15.8717	117.22	0.000
Linear	3	47.6152	15.8717	117.22	0.000
Tool rotation speed	1	19.9632	19.9632	147.44	0.000
Shoulder dia.	1	26.6811	26.6811	197.05	0.000
Pin dia.	1	0.9709	0.9709	7.17	0.020
Residual Error	12	1.6248	0.1354		
Total	15	49.2401			

Statistical significance of each parameter is evaluated using the Analysis of Variance (ANOVA) at 95% confidence level. Analysis of Variance (ANOVA) for shown in Table, DF (degree of freedom), SS (sum of square of deviation), MS (mean square deviation), F (fisher's ratio), P (probability of significance). From this table, it is shown that P-values of tool rotational speed, shoulder dia. and pin dia. are less than 0.05.

Table 8 Analysis of variance table for local heat flux

Analysis of variance for local heat flux: (Response Surface Regression): S = 0.439876, R-sq = 99.56%, R-sq(adj) = 99.46%, R-sq(pred) = 99.04%.					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	530.799	176.933	914.42	0.000
Linear	3	530.799	176.933	914.42	0.000
Tool rotation speed	1	481.990	481.990	2491.02	0.000
Shoulder dia.	1	48.097	48.097	248.58	0.000
Pin dia.	1	0.711	0.711	3.68	0.079
Residual Error	12	2.322	0.193		
Total	15	533.121			

4.4.2. Multi-objective optimization

Multi objective optimization of tool rotational speed, shoulder dia. and pin dia. is done by employing response surface modelling. Fig. 5 shows the results of the multi- objective optimization system. This Fig. 5 represents composite desirability values of responses corresponding to optimal set of parameters. The goal is to find out optimum combination of process parameter for minimization of torque, power and maximization of local heat flux. Optimal tool rotational speed, shoulder dia. and pin dia. evaluated are 600 rpm, 12 mm and 5 mm, respectively.

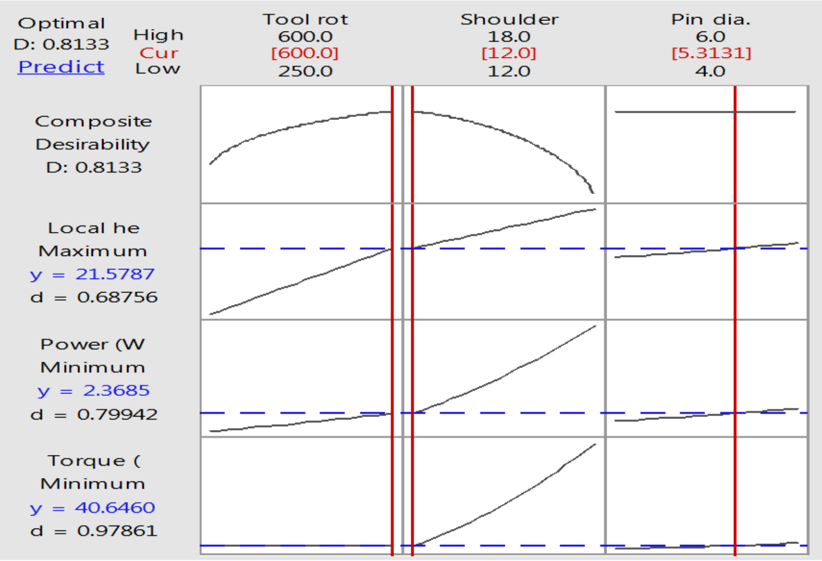


Fig. 5 Variation of torque, power and local heat flux against rotation speed, shoulder diameter and pin diameter

5. Conclusions

The following salient conclusions have been drawn from the present study:-

(1) A mathematical model has been successfully developed to compute heat generation at given tool speed and tool geometry.

(2) The relationship has been developed between tool rotating speed, shoulder diameter, pin diameter and traverse speed for Friction Stir Welding (FSW).

(3) Heat generation increases with the increase in tool speed at given traverse speed where contribution of rotational tool speed is 73-88 % and contribution of translational tool speed is 12-27 %.

(4) The value of heat generation is higher with taper cylindrical pin with that of cylindrical pin.

(5) The optimum value of various parameters responsible for heat generation in FSW are - tool rotating speed = 250 rpm, shoulder dia. = 12 mm and pin dia. = 4 mm. The value of torque will be maximum (38.75 kN-mm) at minimum heat flux (8.375 W/mm^2).

(6) At a given constant traverse speed, temperature increases with increase in rotational speed.

Nomenclature

$Q_{Shoulder}$	heat generation from the shoulder surface (W)	ω	angular speed, or tool rotation rate (rpm)
Q_{Pin}	heat generation from the pin surface (W)	α	angle of FSW pin tool taper (°)
$Q_{Pin\text{-}tip}$	heat generation from the pin tip surface (W)	k	friction coefficient
Q_{Total}	total heat generation (W)	δ	contact state variable (dimensionless slip rate)
Rs	weld tool shoulder radius (mm)	T_m	melting point of the alloy (K)
Rps	weld tool pin radius measured at the shoulder (mm)	T	peak temperature of stir zone during FSW (K)
Rpt	weld tool pin tip radius (mm)	σ	temperature and strain rate dependent flow stress of work piece (MPa)
L_pin	weld tool pin length (mm)	τ_{yield} (τ)	yield shear stress at welding temperature (MPa)
υ	tool angular speed or tool travel speed (mm/min)		

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