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Shahid Chamran
University of Ahvaz

Journal of Applied and Computational Mechanics



Research Paper

Effect of Tool Shoulder and Pin Cone Angles in Friction Stir Welding using Non-circular Tool Pin

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Received April 30 2019; Revised June 23 2019; Accepted for publication June 23 2019.

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Abstract. In friction stir welding frictional heat is generated by the rotating tool, sliding over the stationary plate along the weld centre. Tool being the only source of heat producing member, its geometrical design influences the heat generation rate. In this present work, effects of variation in tool shoulder and tool pin taper angles on thermal history during joining are analysed. Tools with triangular and hexagonal tool pins are used to understand the influence of tool pin shape on process temperature. An analytical heat input model is developed for tools with non-circular tool pins and a comparative study is carried out between the hexagonal and triangular tool pins on temperature distribution using a three dimensional Matlab model. Proposed model is validated through experimental analysis. Apart from this, regression model based comparative study is carried out on the variation in temperature response to the change in tool pin shape, tool shoulder and tool pin taper angle.

Keywords: Tool design, Thermal analysis, Friction stir welding, Non-circular tool pin.

1. Introduction

Friction Stir Welding (FSW) uses the heat produced by the relative motion between rotating tool and a stationary workpiece to be joined. The function of the tool is to not only produce heat but also to mix the material beneath its shoulder during its forward motion along the joint line. Final weld quality depends on parameters like, tool rotation speed, tool transverse speed, tool design and tool tilt angle [1 & 2]. Tool tilt and cone angle affect the material flow considerably which in turn alters the weld quality. Fig. 1, represents the two dimensional view of the workpiece and the tilted tool with cone angle. Normally tilt angle varies from 3° to 0° in which zero value denotes the perpendicular position of the tool without any tilt.

Total heat generation in FSW is because of the friction between the tool and the workpiece as well as the plastic deformation of the material in the stir zone. This indicates that the temperature dependent mechanical properties of the materials to be joined depend on heat generation and metal flow around the tool pin which leads the analysis towards thermomechanical problem. Zero tilt angles make the entire shoulder surface to come in contact with the workpiece and improve the heat generation due to the improvised frictional contact surfaces. But it results inadequate space for the metal flow from the leading edge to the trailing edge which leads to a damaged weld. Increase in tilt angle reduces the frictional heat supply. So, it is necessary to keep the tilt angle in an optimal level to improve the weld quality without altering the frictional heat generation [3].

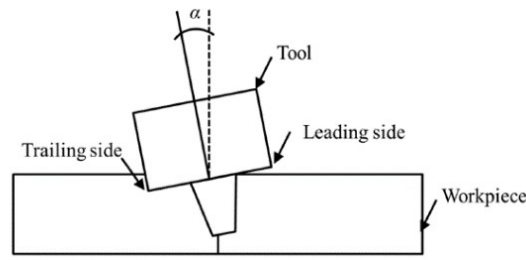


Fig. 1. Tool tilt and cone angle

Although tool tilt angle plays a vital role in material flow, change in tilt angle does not affect heat generation rate much as there is no considerable variation in the tool/matrix frictional contact surface. But the major drawback of tilting the tool is, it leads to uneven temperature raise as the contact pressure varies in trailing and leading edges. This limitation can be eliminated by developing a concave shape tool shoulder which facilitates the required space for the material flow inside the tool shoulder [4]. The outer edge of the tool shoulder always contacts the workpiece which restrict the over flow of the material by allowing it to rotate within the tool boundary [5]. Concave surface area of the tool shoulder depends on the shoulder cone angle. This allows more flexibility of adjusting the contact area by remodifying the shoulder cone angle as per the requirements which improves the ability to weld more complex shapes [6].

Miroslav et al [7] developed an analytical equation to understand the change in heat generation rate with respect to the change in the shoulder cone angle. Durdanovic et al [8] developed a mathematical model to analyse the heat transfer on plunge, dwell and welding stage using a concave shoulder surface. Rajiv et al [9] developed a Matlab model to identify the effects of tool design and other parameters on weld quality. Experimental analysis by Yuvraj et al [10] in friction stir welding using square shape tool pin concluded that 3° cone angle in shoulder produced better weld quality than tools with 1° and 4° cone angle. Similar results are obtained by Krishna et al [11] in friction stir welding using tool with circular tool pin.

The geometrical shape of the tool pin has a direct effect on heat generation and plastic deformation of material during the process [12]. Taper angle of the tool pin changes the shape of the tool pin which modifies the contact surface of the tool/matrix interface and influences heat generation and metal flow rate. Hattingh et al [13] analysed the impact on tool geometry in the tensile strength of the weld joint. In their investigation, force exerted on the tool pin also calculated by varying the tool pin taper angle. Their experimental analysis concluded with a high weld quality and minimum tool opposing force in an optimised tool angle. Apart from experimental analysis, Buffa et al [14] used a continuum based FEM model to identify the role of tool design in heat generation. They identified that the tool pin angle is directly proportional to the heat generation. Their results clarify that increase in pin angle not only enlarges the thermo-mechanically affected zone but also it increases the size of heat affected zone during the process as it increases overall temperature in the stir zone. This reveals that the tool pin angle plays an important role in the post weld quality as it affects the microstructure of heat affected zone through modified heat supply. They also found that the flow of material in the stir zone increases with the increase in pin angle.

These investigations clarify the vital role of tool shoulder angle and pin design along with other process parameters in the weld quality. Although several investigations are done on various tool designs with circular tool pins, limited work has been done in non-circular tool pins. In this present work, a remodified analytical model is developed to identify the heat generation during friction stir welding using tools with tapered tool shoulder along with tapered hexagonal and triangular tool pins. Peak temperature developed during the process is also identified for various tool designs and also a Matlab based numerical analysis is carried out to understand the effects of increase in taper angles of shoulder surface and pin on temperature distribution at different zone which has a direct influence on the post weld properties. Obtained results are validated through experimental results. Apart from this, a statistical model has been developed to understand the effects of geometrical change in tool design on temperature response.

2. Analytical Heat Input Modelling

In Friction stir welding, irrespective of pin geometry, heat supplying surfaces can be divided into tool shoulder/matrix interface (Q_1), tool pin side/matrix interface (Q_2) and tool pin tip/matrix interface (Q_3) as shown in Fig. 2. The heat generated in the contact interfaces for the straight non-circular tool pin can be estimated by [15 & 16],

Heat generated in the shoulder contact surface,

$$Q_1 = \frac{2}{3}\pi(\delta\tau_y + (1 - \delta)\mu_f P)\omega(R_s^3 - R_p^3) \quad (1)$$

Heat generated in the pin tip contact surface,

$$Q_2 = \frac{2}{3}\pi(\delta\tau_y + (1 - \delta)\mu_f P)\omega R_p^3 \quad (2)$$

Heat generated for one pulse from the vertical contact surface is,

$$Q_3 = 3\pi(\delta\tau_y + (1 - \delta)\mu_f P)\omega R_p^2 H_p \quad (3)$$

Here R_s is tool shoulder radius, R_p is tool pin radius, h_p is tool pin height, ω is angular velocity of rotating tool, δ is slip rate, μ_f friction coefficient, P is applied tool force and τ_y is yield stress. These equations are meant for tool with flat shoulder and straight tool pin with zero taper angle. It has to be remodified for the tool with tapered shoulder and tool pin as shown in Fig. 3.

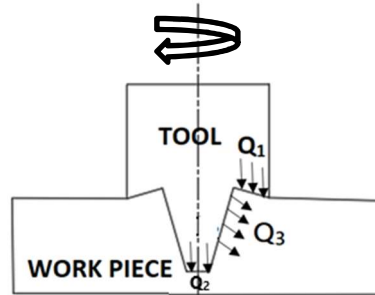


Fig. 2. Heat diffusion interfaces

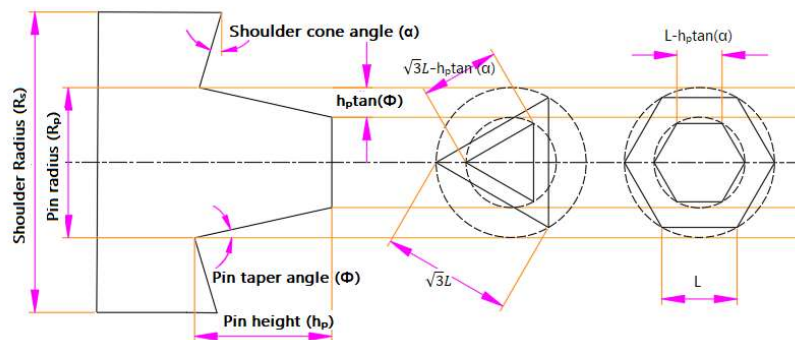


Fig. 3. Modified tool design with shoulder and pin taper angle.

For both triangular and hexagonal tool pin geometries, heat generated at the tapered shoulder/matrix interface remains same [17] and it is given by,

$$Q_1 = \frac{2}{3}\pi\omega(\delta\tau_y + (1 - \delta)\mu_f P)(R_s^3 - R_p^3)(1 + \tan \alpha) \quad (4)$$

Here α is the shoulder cone angle. Heat generation at other two contact surfaces varies with respect to the pin geometry. So, it requires modifications in Eqs. 2 & 3 according to the pin shape. While estimating heat generated by the pin tip, radius of the pin varies with respect to its shape from top to the bottom.

At the pin tip (ref Fig.3),

$$\text{Minimum value of } R_p = R_p - h_p \tan(\alpha) \quad (5)$$

In this equation R_p can be rewritten according to the pin shape as [18], $R_p = \frac{l}{\sqrt{3}}$ for triangular shape and $R_p = l$ for rectangular shape, where l is the side length of the pin. Similarly, the inclination of pin side due to the pin taper angle (ϕ) has to be considered on the estimation of heat generation along the pin side

$$\text{Slant side of pin} = \frac{h_p}{\cos(\phi)} \quad (6)$$

By replacing R_p and h_p in Eqs. 2 & 3 with minimum value of R_p and slant length h_p , for triangular shaped tool pin. At tool pin tip/matrix interface heat generation is,

$$Q_2 = \frac{2}{3}\pi\omega\tau_c(\delta\tau_y + (1 - \delta)\mu_f P)\left(\frac{l}{\sqrt{3}} - h_p \tan \phi\right)^3 \quad (7)$$

At tool pin side/matrix,

$$Q_3 = \frac{1}{2}\omega\tau_c(\delta\tau_y + (1 - \delta)\mu_f P)l^2\left(\frac{h_p}{\cos \phi}\right) \quad (8)$$

For hexagonal shaped tool pin

At tool pin tip,

$$Q_2 = \frac{2}{3} \pi \omega \tau_c (\delta \tau_y + (1 - \delta) \mu_f P) (l - h_p \tan \phi)^3 \quad (9)$$

At tool pin side,

$$Q_3 = 3 \omega \tau_c (\delta \tau_y + (1 - \delta) \mu_f P) l^2 \left(\frac{h_p}{\cos \phi} \right) \quad (10)$$

Here, l is the tool pin side length and ϕ is the taper angle of the tool pin as shown in Fig. 3. The maximum temperature raise during the process, analytically can be estimated as [17],

$$T = \left(0.156 \times 10^{-3} \times \left(\frac{Q_1 + Q_2 + Q_3}{V_w} \right) + 0.54 \right) + T_s \quad (11)$$

Here, T is the maximum temperature during the process, V_w is the welding velocity and T_s is the solidus temperature of the parental metal. In this modelling total heat supply ($Q_1 + Q_2 + Q_3$) corresponding to the pin shape is calculated using the opt equations from Eqn.4 to Eqn.11 considering full sliding condition ($\delta = 1$) and the value of friction coefficient taken as 0.5 [16].

3. Numerical Modelling

Three dimensional thermal model has been developed in Matlab to estimate the temperature gradient at various distances in x, y and z directions with respect to the tool rotation axis. Friction stir welding in Aluminium alloy 6061-T6 is considered for the analysis of temperature distribution. In order to estimate the maximum temperature raise during the process, Rosenthal equation for moving heat source is used [18],

$$T = \left(\frac{Q_{Total}}{2\pi K t} \right) e^{\left(\frac{-U_w \xi}{2\alpha} \right)} K_0 \left(\frac{U_w}{2\alpha} r \right) + T_0 \quad (12)$$

Here, $r = \sqrt{\xi^2 + y^2 + z^2}$, α is thermal diffusivity, K_0 is modified Bessel function, t is thickness of the plate in z direction, T_0 is initial temperature of the plate to be joint and U_w is speed of the moving heat source which will be equal to the welding speed (V_w) for the current analysis. In this modelling the heat supply is assumed to be a moving point source and total heat supply corresponding to the pin shape is calculated analytically using the remodified equations (Eq. 4 to Eq. 11). Change in the thermal properties with respect to the change in temperature is neglected and the entire analysis is done in welding stage in which heat transfer is under quasi steady state [19]. Peak temperature developed during the process depends on the weld velocity and it reduces when the welding speed increases. In this Matlab based numerical model point heat source is assumed and the variation developed on the temperature field in advancing side and retreating side is neglected as the difference is low [7].

4. Experimental Procedure

Aluminium alloy AA 6061-T6 plates with dimension 300mm X 150mm X 6mm are joined in this experimental analysis using HURCO VMX24 vertical machining centres. Mechanical and thermal properties of the material are given in Table 1. Tools made with hardened H13 tool steel material has 50-55 HRC. Eight trails of joining were done with eight different tools in which four tools with triangular tool pin and four with hexagonal tool pin profile. In order to identify the effects of shoulder cone angle, experiments were carried out with tools having 1° and 4.5° tapered shoulder in which tool pins profiles (both triangular and hexagonal) are made straight without taper.

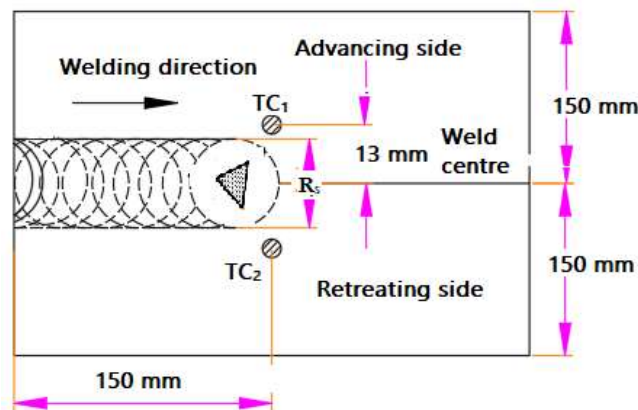


Fig. 4. Layout of experiment

Table. 1. Properties of AA6061-T6

Density (Kg/m ³)	Hardness number (BHN)	Thermal conductivity (W/mK)	Specific heat capacity (J/KgK)	Thermal expansion (10 ⁻⁶ /°C)	Solidus temperature (°C)
2700	95	167	896	23.6	582

Table. 2. Process parameters

Property/parameter	Value
Shoulder radius (mm)	9
Circumscribed pin radius (mm)	3
Height of the pin (mm)	5.4
Workpiece thickness (mm)	6
Applied force (kN)	9
Tool rotation speed (rpm)	900
Initial temperature of workpiece (°C)	25
Weld velocity (mm/min)	80

Another four trials were done using flat shoulder tools with 5° and 15° tapered triangular and hexagonal pin profiles. To maintain uniform swept volume during rotation, the lengths of the tool pin side are selected as 5.2mm for triangular and 3 mm for hexagonal. Other input parameters adopted for the joining process is given in Table 2. To obtain the temperature, thermocouples are fixed at a distance of 13mm from the joint and at a distance of 150 mm from the starting point. Two thermocouples (TC₁ & TC₂) are placed in the given location as shown in Fig. 4. to observe the temperatures in advancing and retreating sides. The average of these two is taken in order to consider the temperature variation on both sides.

5. Results and Discussions

5.1. Effects of shoulder cone angle

The tool pins were designed straight to analyse the effects of shoulder cone angle on temperature gradients in different points of parental metal. Variation in effective heat input (total heat generation/welding speed) corresponding to the change in shoulder cone angle is calculated analytically. With respect to the calculated heat input, possible peak temperature raise during the process is estimated and given in Table 3 for triangular and hexagonal pin profiles.

Table. 3. Effect of tool shoulder cone angle in heat supply and peak temperature

Tool-pin shape	Shoulder cone angle	Pin cone angle	Q _{Total} (Eff) (J/mm)	Peak Temperature (analytical) (°C)	Temp. at 13mm distance (Numerical) (°C)	Temp. at 13mm distance (Exp) (°C)		
						TC ₁	TC ₂	$\frac{TC_1 + TC_2}{2}$
Triangular	1	Straight	868.60	324.8	236.9	232.2	227.4	229.8
	4.5	Straight	920.86	332.03	243.5	245.3	237.9	241.6
Hexagonal	1	Straight	917.12	331.51	242.8	239.7	234.7	237.2
	4.5	Straight	972.30	339.13	254.1	250.7	245.1	247.9

Microstructure analysis done by Ramanjaneyulu et al [20] clearly indicates that although the tool with triangular tool pin generates comparatively less heat than the tool with hexagonal tool pin, it produces finer grains in the stir zone. Unlike tools with circular tool pins, these non-circular tool pins have vertical plane surface which is equal to the number of sides in the tool pin. These vertical surfaces produce pulses during their rotation which increases the rate of flow at the material under the tool shoulder and around the tool pin in the Stir zone. But irrespective of pin shape, all occupies cylindrical volume called swept volume during rotation [21]. Actual volume occupied by the triangular pin during rotation is lesser than that of the hexagonal tool pin. The difference between the actual volume and swept volume is comparatively high for triangular tool pin than the hexagonal too pin which is an indication that the material undergoes higher strain on the usage of triangular tool pin. This higher strain rate is responsible for the finer grain size in Stir zone and it improves the mechanical properties in the thermomechanical affected zone. But on the other hand, these extra strain rates produced during the rotation results extra reaction force in the surfaces of the tool pin [22]. Triangular shape tool pin undergoes comparatively higher opposing force for the forward motion along the weld line during welding stage. Because of the higher transverse force tool life is reduced and as the weaker part in the tool, tool pin damages. To improve the tool life, it is mandatory to reduce the transverse force given by the flow material under the tool shoulder. This can be achieved through the increase in process temperature. Raise in temperature in the stir zone reduces the strength of the material and in turn reduces the opposing force. Three dimensional analysis of temperature distribution shown in Fig. 5 suggests that tool shoulder cone angle of 4.5° improves the heat generation rate and increases the temperature at all the points in the stir zone and the maximum temperature that can be achieved is estimated as 332°C. For the hexagonal tool pin in order to decrease the excess heat travelling in the parental metal, it is necessary to select the tool shoulder cone angle which produces lesser heat supply. Numerical analysis done on the temperature distribution on

the usage of hexagonal tool pin indicates that the shoulder taper angle of 1° produces lesser heat supply. The experimental investigation done on the temperature distribution shows that the minimum temperature of 237.2°C is recorded on the usage of 1° shoulder taper angle for hexagonal tool pin in the heat affected zone. The variation in heat supply and corresponding variations in the temperatures are given in the Table.3. This clearly indicates that the tool with less shoulder cone angle reduces heat diffusion through the workpiece as it reduces intensity of heat supply.

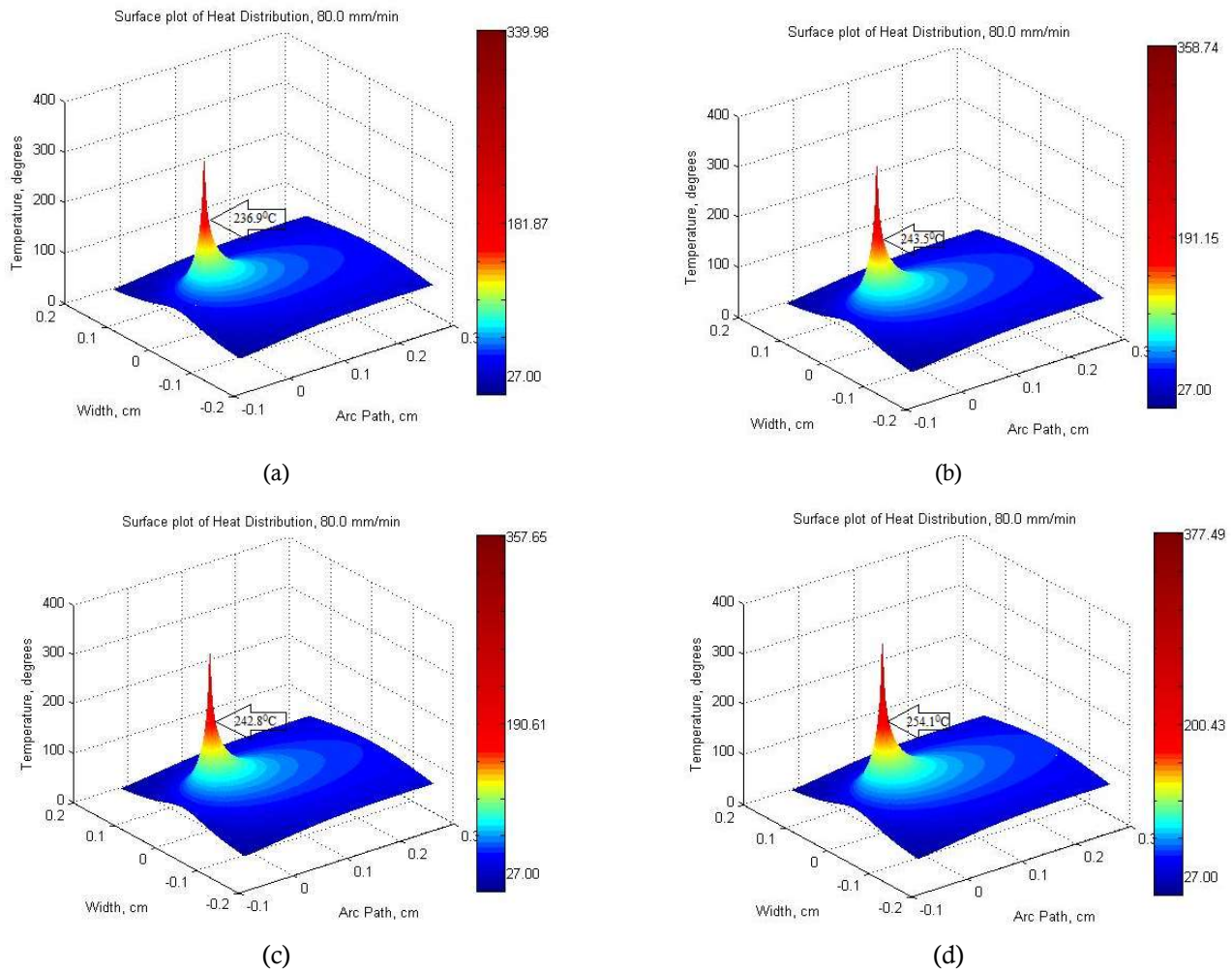


Fig. 5. Numerical temperature distribution analysis for different shoulder cone angle

Tool with triangular tool pin and shoulder cone angle (a) 1° and (b) 4.5°

Tool with hexagonal tool pin and shoulder cone angle (c) 1° and (d) 4.5°

5.2. Effects of tool pin taper angle

In order to investigate the effects of tool pin taper angle, tool shoulder is designed flat for the analysis. Analytically calculated heat supply, maximum temperature during the process and numerically estimated temperature at a specific location are compared with experimentally recorded temperature in the same location during welding stage for the selected process parameters for different tool pin taper angles are listed in Table 4.

Table 4. Effect of tool pin taper angle in heat supply and peak temperature

Tool-pin shape	Shoulder cone angle	Pin cone angle	Q_{Total} (Eff) (J/mm)	Peak Temperature (analytical) ($^\circ\text{C}$)	Temp. at 13mm distance (Numerical) ($^\circ\text{C}$)	Temp. at 13mm distance (Exp) ($^\circ\text{C}$)		
						TC_1	TC_2	$\frac{TC_1 + TC_2}{2}$
Triangular	Flat	5	839.03	320.73	230.3	230.1	224.3	227.2
	Flat	15	823.55	318.6	227.1	224.2	218.4	221.3
Hexagonal	Flat	5	886.90	327.34	238.7	236.3	231.9	234.1
	Flat	15	872.92	325.41	237.3	234.5	231.1	232.8

Shoulder radius (R_s) does not depend on pin shape and irrespective of pin shape, it remains same. So, heat generated along the tool shoulder/matrix interface is same for all tool designs given in Table 4. But pin radius (R_p) depends on tool taper angle. The radius changes from root and it attains minimum value at the tool pin/matrix contact surface. When the taper angle increases its value decreases at the bottom contact surface. On the other hand, tool pin side length increases

when the taper angle increases. These changes influences heat generation rate on their contact surfaces. The changes in total heat generation corresponding to the change in pin shape and taper angle is given in Table 4.

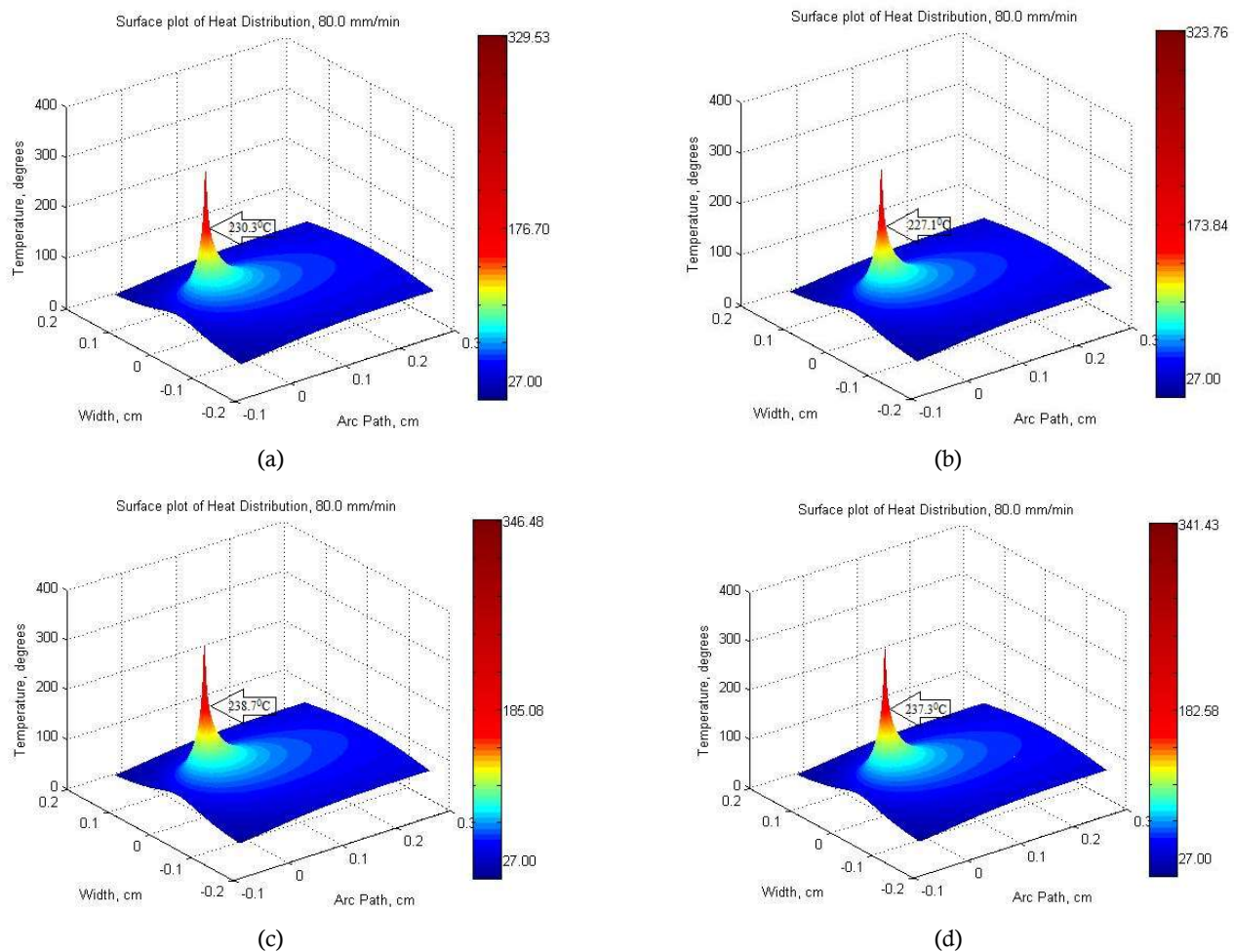


Fig.6. Numerical temperature distribution analysis for different tool pin taper angles

Tool with triangular tool pin and pin taper angle (a) 1° and (b) 4.5°

Tool with hexagonal tool pin and pin taper angle (c) 1° and (d) 4.5°

Mechanical properties in the stir zone and thermomechanical affected zone are not only dependant on the temperature but also on the material flow rate as mentioned earlier. So, the post weld properties on those areas cannot be predicted with thermal history alone. Especially with non-circular tool pins, as they produce different flow rate depending on the geometrical shape of the pin, it is mandatory to analyse the microstructure along with the temperature gradient to conclude the resulted properties after the joining process. But heat affected zone developed in the parental metal during the process is completely independent of the plastic deformation of material and it depends only on the thermal history developed in this zone. In friction stir welding, failure happen in heat affected zone as it exhibits degraded post weld properties because of its coarse grain structure [23]. Fig. 6. shows the three dimensional temperature distributions at various distances along the parental metal during the process. Decreasing the size of heat affected zone can be achieved through the reduction of heat transfer from the stir zone to the heat affected zone. This can be achieved by controlling the heat generation rate through the increase in tool pin taper angle and by the decrease in shoulder cone angle. The reduction in temperature in stir zone increases the strength of the material and in turn increases the transverse force in the tool pin. But the increase in taper angle reduces the tool pin /matrix contact surface and results in the lesser surface stress in the tool pin surfaces. So, tool pin taper can be increased in order to increase the tool life. Especially on the usage of triangular pin, although it results in better weld quality, premature failure of pin is the major problem. The increase in pin taper angle does not influence rate of heat generation more comparing with change in shoulder taper angle. So, a maximum of 15° pin taper angle can be adopted while designing triangular tool pin in the view of increasing its tool life with a minimal compromise in heat generation rate.

5.3. Quantitative prediction through statistical estimation

Analytically derived correlations (Eqn. 4 to 11) are useful to know the degree and direction of relationship between the chosen variables in the tool design. Regression analysis on the other hand, may be useful in the future addition of more complex independent variables like number of threads in the tool pin. Experimental and numerical analyses clearly indicate that the process temperature is also a function of different variables related to the tool design and it can be

expressed for a tool with polygonal shaped tool pin as,

$$T = f(\alpha, \varphi, n) \quad (13)$$

where T is temperature response, α is the shoulder taper angle, φ is pin taper angle and n represents the number of sides in the tool pin. For the current analysis, as three variables are selected, graphical representations are not possible. It will be meaningful to predict an average relationship between dependent and independent variable through multiple regression analysis using direct method. This could be expressed as,

$$T = a + b_1(n) + b_2(\tan(\varphi)) + b_3(\tan(\alpha)) \quad (14)$$

Here a is the intercept of the plate, b_1 , b_2 and b_3 are regression coefficients that represents the expected change in temperature response per unit change in n , φ and α respectively, when other two variables are held constant. Based on the obtained values (Tables 3 & 4), the values of intercept and coefficient of restitutions are estimated and given in Tables 5 & 6.

Table. 5. Regression analysis data

	Coefficients	Standard Error
Intercept	219.1289	2.066621
No sides	2.675	0.381352
Pin taper	-14.459	6.561803
Shoulder taper	170.8585	22.18579

Table. 6. Summary output

Regression statistics	
Multiple R	0.989209609
R Square	0.97853565
Adjusted R Square	0.962437387
Standard Error	1.617940595
Observations	8

This regression analysis results the mathematical model for temperature response and it can be expressed as,

$$T = 219.1289 + 2.673(n) - 14.459(\tan(\varphi)) + 170.8585(\tan(\alpha)) \quad (15)$$

From the summary output listed in Table.6, it can be understood that the value of coefficient of determination (R^2) is nearer to 1 and it explains the reliability of the regression correlation. Obtained coefficient of restitution for the selected variables indicates that for the pin taper angle, attained temperature raise provides with a negative response and for the other two variables it undergoes positive response. The lower value of b_1 comparing with the values of b_2 and b_3 concludes that the impact of pin taper angle on temperature response is comparatively low than the other two. Experimentally attained temperature response trend lines for various tool designs are shown in Fig.7. The negative and positive slopes of the lines corresponding to the change in variables indicate that the mathematical model derived through regression analysis is well aligned with the experimentally recorded values.

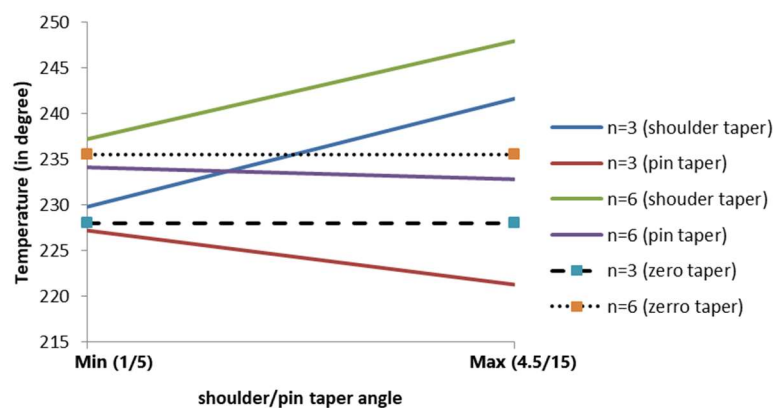


Fig.7. Experimentally obtained temperature response trend lines for different tool designs.

6. Conclusions

In this analysis, a three dimensional Matlab model has been developed to register thermal history in the parental metal during the process using a remodified analytical heat input model applicable for different tool geometry. An experimental analysis is made and the numerically obtained results are validated for different tool designs. The obtained results conclude that the heat generation rate is directly proportional to the shoulder cone angle and inversely proportional to the pin taper angle irrespective to the tool pin shape. Regarding the geometrical shape of the tool pin, the



intensity of heat generation is directly proportional to the number of sides in the tool pin. It can be concluded that tool with hexagonal pin can be designed with lesser shoulder cone angle and higher tool pin taper angle to control the amount of excess heat diffusion through the workpiece. On the other hand, tool with triangular pin can be designed with higher shoulder cone angle and higher pin taper angle to reduce temperature gradient and transverse force in the stir zone in the view of improving tool life. Trend lines obtained on the temperature response for various tools suggest that the impact of shoulder cone angle on heat generation is comparatively higher than the pin taper design.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The authors received no financial support for the research, authorship and publication of this article.

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