

Parametric Analysis of Friction Stir Welding Using Finite Element Tool

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ABSTRACT: Friction stir welding is a relatively novel welding technique invented in welding institute UK in 1991, which is further been advanced and are current now been used in joining pure alloyed material such as aluminium, copper, etc however, joining this material are quite difficult but due to its significant attribute of FSW has numerous application in Automotive, space, marine, and industrial sector. During FSW process heat is generated due to motion of tool which in term fuses the work specimen and due to stirring action the work-piece is welded.

In this paper a computational 3 Dimensional transient model is developed using ANSYS 14.5 where the thermal history during FSW of pure copper has been studied. A parametric analysis has been carried out in order to examine the temperature distribution along the weld pure copper plate. The two process parameters i.e. transverse speed and rotational speed are varied and the temperature profile are drawn and compared with experimental work. In additional to this the effect of these parameters on heat loss has also been scrutinized which facilitates in optimizing FSW process.

KEYWORDS: Temperature profile, Convective and Radiative heat loss, Transverse and Rotational Speed.

I. INTRODUCTION

Friction stir welding is advanced solid state non consumable joining technique. Due to its significant advantages over other fusion process such a Joining of non-fusion weld-able alloys, decreased distortion and advanced mechanical properties of weld-able alloys joints as a result of the pure solid-state joining of metals. Therefore, it is widely been used in many industrial sectors such as aerospace, marine, railway, automotive, land transportation, etc. Conventionally, in FSW force is applied through rotating pin tool to delve into the plates to be welded and traveled along their contact line as shown in figure 1. During the welding process, heat is generated by means of frictional contact between rotating tool and the work specimen which leads to soften the material. However, nor melting takes place during the FSW process, moreover it interesting to know the process performed at much lower temperatures than the other conventional welding techniques. On account of the highest temperature is lower than the melting temperature of the material, FSW yields fine microstructure.

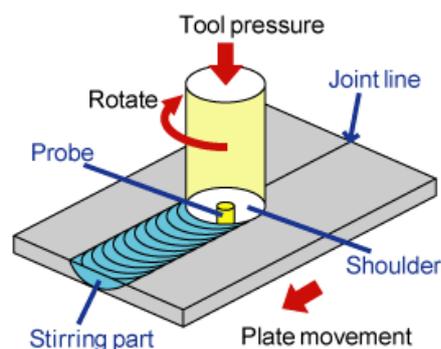


Figure 1 Friction stir welding

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II. LITERATURE SURVEY

In 1991 the welding institute of UK innovates a new weld process which is named as Friction stir welding (FSW) by its name itself, it signifies that process can be accomplished by the heating generation between the tool and the Workpiece due to friction and plastic deformation of workpiece take place. [1] Later with the progressive develop the field of material technology and computation plentiful research has been done via experimentally and computationally.

Rodes et al 1997 7075 Al plate has been successfully joined by friction stir techniques. Unlike fusion welding, this is a solid-state process with no evidence of melting. The weld is characterized by a recrystallized nugget having a 2-4 pm grain size.

Chen and Kovacevic 2003 present a three-dimensional model based on finite element analysis to study the thermal history and thermo mechanical process in the butt-welding of aluminum alloy 6061-T6. The model incorporates the mechanical reaction of the tool and thermo mechanical process of the welded material. The heat source incorporated in the model involves the friction between the material and the probe and the shoulder

Song and Kovacevic 2003 present 3D heat transfer model in which; a moving coordinate is introduced to reduce the complexity of modeling the moving tool. The obtained results are verified with the experimental result and are within acceptable limit and conclude that preheating of the work piece is beneficial to FSW

Colegrove and Shercliff describes the application of the computational fluid dynamics (CFD) code, FLUENT, to modelling the 3-dimensional metal flow in friction stir welding (FSW). A standard threaded tool profile is used for the analysis and features such as the tool rake angle, heat generation and heat flow are included. The primary goal is to gain a better understanding of the material flow around a complex FSW tool and to demonstrate the effect of the tool rake angle, and weld and rotation speed.

Zhang et al. 2005 Two-dimensional results of the material flow patterns and the residual stresses are presented. The flow of metal during FSW is investigated using tracer particles. It is shown that the flows on the advancing side and retreating side are different. After several rotations the material which is rotating around the nib sloughs off in its wake of the pin, primarily on the advancing side. The residual stresses of the welded plate are investigated in this analysis.

Zhang et al. 2007 Material flow in friction stir welding (FSW) under different process parameters is simulated by using the finite element technique based on the nonlinear continuum mechanics. Results indicate that the distribution of the equivalent plastic strain correlates well with the distribution of the microstructure zones in the weld. It seems that there is a quasi-linear relation between the change of the axial load on the shoulder and the variation of the equivalent plastic strain.

Liechty and web 2008 develop three dimensional numerical model in order to investigate frictional heating and material flow for two different boundary condition i.e. sticking constant velocity and a slipping variable shear stress model. It has found that the variable shear model is superior to a sticking condition.

Arora et al. 2009 solve the equations of conservation of mass, momentum and energy for FSW of AA2524 aluminum alloy model are developed which predicts the torque, power requirement and stir zone for a full range of welding speeds and tool rotational speeds when the heat transfer coefficient and the friction coefficient values were set.

Edward Et al. 2010 examine that effect of weld tool travel angle for butt welded 5083-H111 aluminum alloy in the presence of joint gaps using industrial robot. On increasing gap higher weld angle should be used in order to achieve higher joint efficiencies.

Wang and Colegrove 2013 presents a novel for characterizing the contact conditions that occur during FSW method by explaining the outcomes of mechanical and thermal during stick and slip condition. The proposed model yields more realistic heat generation estimate, as validated by the experimental thermal measurements.

Cartigeyen et al. 2014 perform numerical and experiment heat generation simulation with different combination of process parameters. The obtained grain structures are further examined by Optical microscope (OM) micrographs and reveal that grain structure strongly depends upon the heat generation.

Hamed et al. 2014 develop numerical model for predicting temperature distribution, plastic strain distribution and material flow in copper plates. A commercial software DEFORM-3D has been employed which is incorporating the Arbitrary Lagrangian Eulerian (ALE) formulation.

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III. MATHEMATICAL MODELLING

During welding process the tool is allowed to move at a constant speed along the weld line by means of moving coordinate system. Because of this it is not necessary to develop the obscured stir process close to the pin, thus it makes the model easier.

Heat generation in FSW is generally governed by two means. Firstly, due to friction & Secondly due to plastic deformation during the process heat is transmitted to work piece and follows Fourier's law of heat conduction.

In numerical analysis, the transient temperature field (T), which is a function of time (t) and along with the spatial coordinates (x, y, z), is approximated by the 3-D nonlinear heat transfer equation in which the moving Cartesian coordinate system with a positive y -direction moving tool is written as

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) + \dot{Q} = \rho C_p \left(\frac{\partial T}{\partial t} - V_r \frac{\partial T}{\partial y} \right) \quad (1)$$

where ρ , C_p and k refer respectively to density, specific heat and directional thermal conductivity of the workpiece material, \dot{Q} is the rate of heat generation and V_r is the transverse speed of the tool. It should be noted that the interface thermal resistance between two plates is neglected here. The boundary condition for the FSW thermal model is specified as the Advances in Friction Stir Welding and Processing surface interaction of the solution domain. The initial condition for the calculation is expressed as

$$T(x, y, z, 0) = T_i \quad (1a)$$

where T_i is the ambient temperature at time $t = 0$. The boundary interaction of the solution domain is schematically represented in Figure 2.

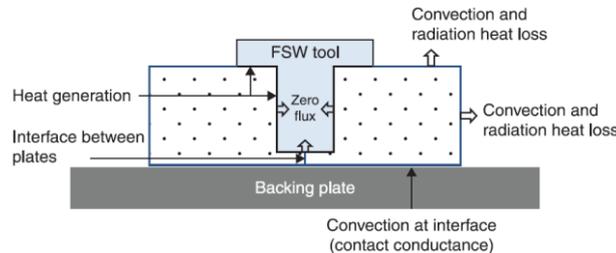


Figure 2 Schematic of solution domain and boundary interactions [12]

Where T is the temperature, c is the heat capacity, r is the density, k is the heat conductivity, and v is the tool moving speed.

The heat generated at the tool shoulder/workpiece interface is assumed the frictional work in this model. The local heat generation can be calculated by the following expression

$$q_r = \frac{3Q_r}{2\pi(r_0^3 - r_i^3)} \quad (2)$$

$$Q_r = \frac{\pi\omega F \mu (r_0^2 + r_0 r_i + r_i^3)}{45(r_0 + r_i)} \quad (3)$$

Where R_i is the distance from the calculated point to the axis of the rotating tool, n is the rotational speed of the tool.

The coefficient of the friction is believed to vary during the FSW process; the detail of the variation is still not clear so far. An effective coefficient of friction is assumed in this model.

The heat generated by the tool pin consists of the following three parts: (1) heat generated by shearing of the material; (2) heat generated by the friction on the threaded surface of the pin; and (3) heat generated by friction on the vertical surface of the pin. the heat generated from the pin is expressed as.

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$$Q_{pin} = 2\pi r_i h k \bar{Y} \frac{V_m}{\sqrt{3}} + \frac{2\pi \mu r_i h k \bar{Y} V_{ri}}{\sqrt{3(1+\mu^2)}} + \frac{4F \mu V_m \cos \theta}{\pi} \quad (4)$$

Where,

$$\theta = 90^\circ - \lambda - \tan^{-1}(\mu), \quad (5)$$

$$V_m = \frac{\sin \lambda}{\sin(180^\circ - \theta - \lambda)} v_i, \quad (6)$$

$$V_{ri} = \frac{\sin \lambda}{\sin(180^\circ - \theta - \lambda)} v_i \quad (7)$$

$$v_i = \omega r_i \quad (8)$$

v_i , and $v_i = r_i \omega$. r_i is the radius of the tool pin, h is the thickness of the workpiece, \bar{Y} is the average shear stress of the material, λ is the helix angle of the thread and F is the translation force during the welding, and μ is the friction coefficient. Because the tool pin is assumed to be a cylinder with no thread, only the first item in Eq. (4) is calculated as the heat input from the tool pin.

Heat loss from the Work Piece

In order to determine the thermal history of the workpiece in friction stir processing heat transfer coefficient of work specimen play a crucial role. Convective and radiative heat loss to the ambient on all workpiece surfaces (except for the bottom), the heat loss (q_s) is obtained by equation (9)

$$q_s = \beta(T - T_o) + \epsilon \sigma (T^4 - T_o^4) \quad (9)$$

where T is absolute temperature of the workpiece in K, T_0 is the ambient temperature (300 K), β is the convection coefficient, ϵ is the emissivity of the plate surfaces, and σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$). Based on the previous studies [14], an elevated overall heat transfer coefficient has been presumed in order to account for the conductive heat loss throughout the bottom surface of FSPed sheets. The heat loss through bottom surface was modeled approximately by using heat flux loss by convection q_b given by equation (10).

$$q_b = \beta_b (T - T_o) \quad (10)$$

where β_b is an equivalent fictitious convection coefficient

IV. METHODOLOGY

The equation of motion for friction stir process is solved by using finite element tool ANSYS 14.5. However, the direct simulation of the welding processes is not possible; therefore coupling of various analysis models has been done i.e. Transient Structural + Transient Thermal. Using Transient Structural module appropriate downward force is applied and the temperature and time dependency has been calculated using Transient Thermal. First the Geometrical Model has been developed which includes moving tool along the welding line between two copper plates. After that model is discretized by mapped meshing and the boundary conditions are applied. The simulating parameters are given in table 1

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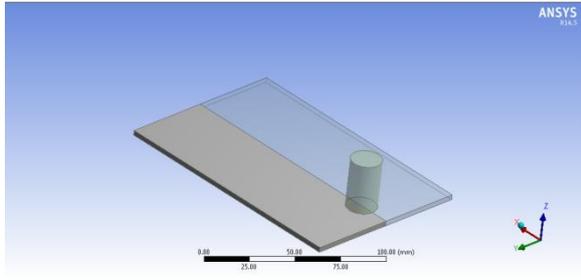


Figure 3 Geometrical Model

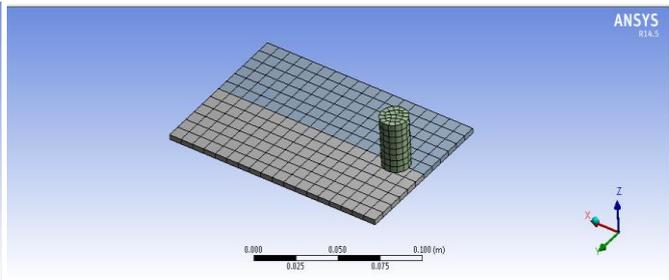


Figure 4 Mesh model

Table 1 Material Properties Ref. [10]

Work Piece (Pure Copper)	Value	Tool High carbon high chromium (HCHCr)	Value
Density	8960 Kg/m ³	Density	7700kg/m ³
Elastic Modulus	110-128GPa	Elastic Modulus	190-210GPa
Poisson's Ratio	0.34	Poisson's Ratio	0.27-.030
Melting Point	1084.62°C	Melting Point	1421°C
Coefficient of Thermal Expansion	16.5/°C	Coefficient of Thermal Expansion	10.4x10 ⁻⁶ /°C
ε, emissivity of the plate surfaces	0.65		
μ is the frictional coefficient of material	0.36		
βb equivalent fictitious convection coefficient	170W/m ² K		
Convective coefficient	17W/ m ² K		

V. RESULT AND DISCUSSION

Validation

The governing equation of a friction stir welding is solved, numerically as well as computation using finite element analysis, which is coupled with two module structural and thermal transient mode in order to compute the temperature distribution along the weld surface during the Friction stir process. The result are obtained in the order of 107 so that the accuracy of the computational model is suitably been verified and validated with the available literature.

The precision of the obtained result are confirmed by comparing the computational result with Experiment Cartiguevena [10], analytical and FEA results.

Table 2 Validation of Peak temperature Distribution for Various rotational Speed

Process Parameters	Peak Temperature °C		Percentage Difference
	Experimental Ref.[10]	Present FEA (ANSYS)	
500rpm & 30mm/min	310.5	322.4504	3.7761%
700rpm & 30mm/min	478	487.3363	1.9343%
1000rpm & 30mm/min	630	645.5663	2.4407%

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In table 2 and figure 4 (a,b) shows the validation of computed FEA result obtained from the ANSYS tool. It observed that the acquired results of the FSP with different process parameters shows good agreement with the FEA and the Experimental results of available literature. The small variation in results is due to variation in mesh sizing, operating condition, geometrical parameters, etc. but the obtained result shows the similar fashion so that the results are suitably validated.

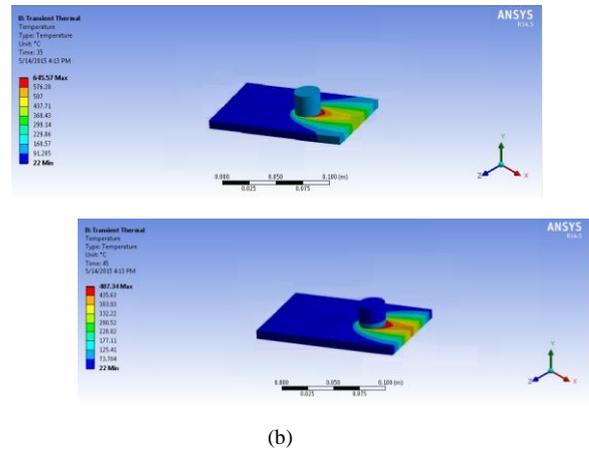
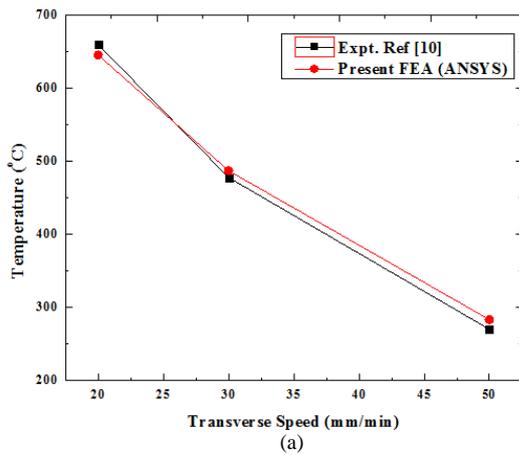


Figure 4 (a) Validation of Peak temperature Distribution for Various Transverse Speed and (b) Validation of peak Temperature for Process Parameter 1000rpm & 30mm/min and 30mm/min & 700 rpm

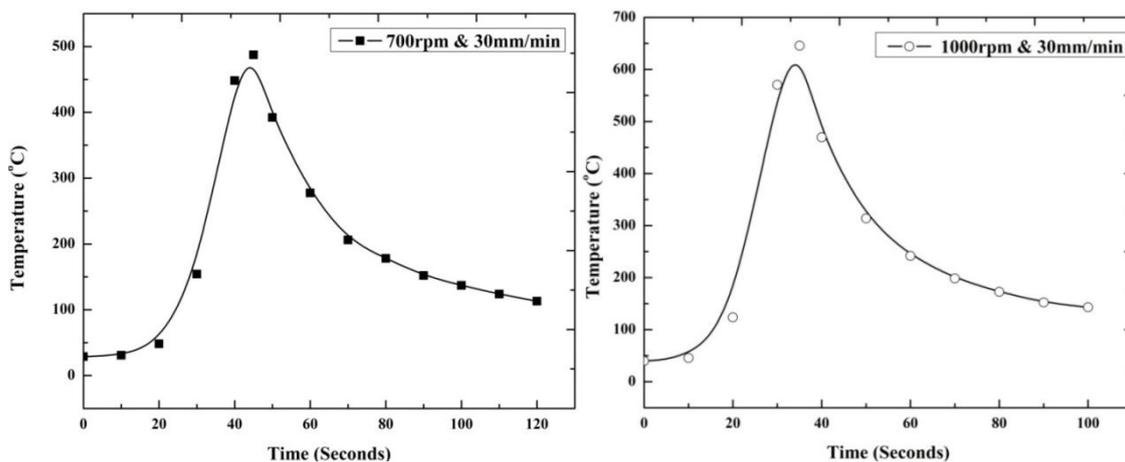


Figure 5 Simulation results of temperature profiles for pure copper at 700rpm and 1000 rpm (rotational speed and 30mm/min (Transverse speed))

Figure 5 illustrates the validation of peak temperature profile for different process parameters in which two different sets of simulation has been performed. By keeping constant transverse speed, rotational speed is increased; while rotational speed is kept constant and the transverse speed is increased simultaneously. It has observed that rotation of tool leads to mixing and stirring of material around the rotating pin. Moreover, translation of tool shifts the stirred material from front to back of the pin and completes the welding process. Higher tool rotational speed causes higher temperature due to higher friction heating and leads to more intense stirring and mixing of material. Furthermore, it should be addressed that frictional coupling of tool surface with work specimen is going to govern the heating. Nevertheless, considerable increase in heating with increasing tool rotation rate is not expected as the coefficient of friction at the interface will alters with increasing tool rotation rate.

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In figure 5 it has observed that at a constant transverse speed of 30mm/min, the peak temperature and the heat generation significantly increases as the rotational speed increases, this is due to increased strain rate and plastic dissipation in the stir zone. With increasing 40 %-42.85 % of rotational speed from 500rpm leads to significant change in the thermal history where the maximum temperature of 487.33⁰C is observed at 700 and 645.5663⁰C for 1000rpm.

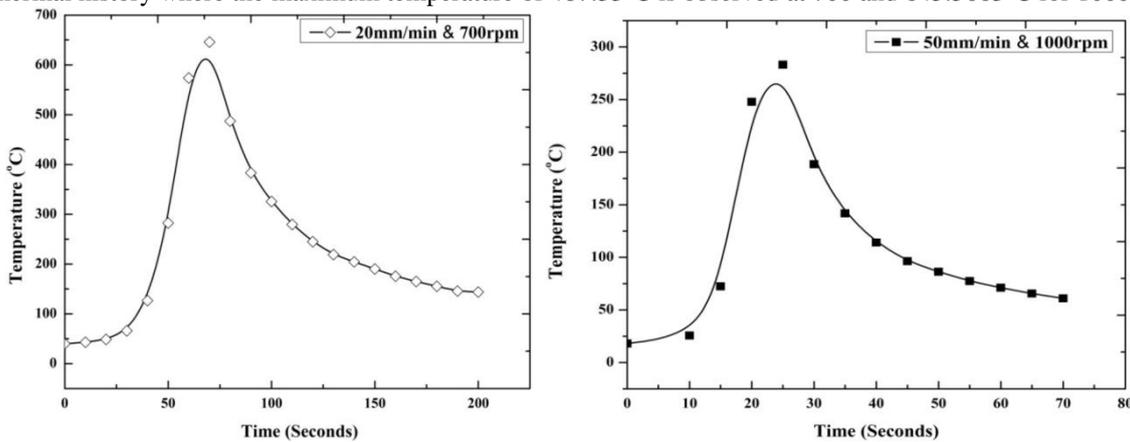


Figure 6 Simulation results of temperature profiles for pure copper at 20mm/min (Transverse speed) and 700rpm (rotational speed)

Figure 6 illustrates the effect of variation of transverse speed on the temperature profile of the workpiece. It has observed that on increasing transverse speed temperature at the stir zone radically decreases. Moreover, the noteworthy variation has also been observed in the thermal history. In figure 6 maximum temperature of 645.7882⁰C is addressed at 20mm/min & 700rpm. These observations were consistent with other studies [11].

From these it can be concluded that softening degree of the stir zone was affected by the peak temperature and the process duration at high temperature. Furthermore, the cooling rate at 50mm/min is higher in comparison with other two process parameter i.e. 20 and 30mm/min. The exposed interval at three process parameters (20, 30 and 50 mm/min – 700 rpm) were 204, 120.1 and 71.5 second respectively. From this it can be reveals that at higher transverse speed reduces the process timing and consequently the workpiece will stay less time at higher temperatures.

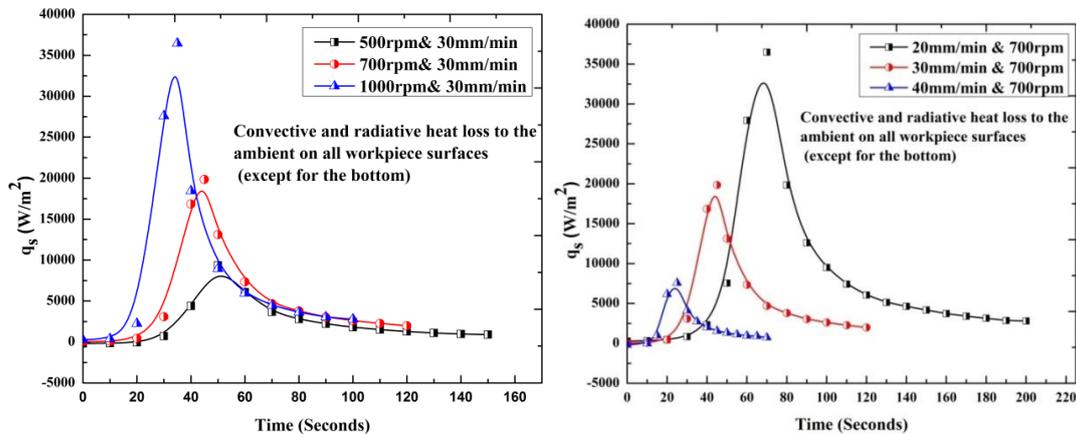


Figure 7 Comparative Heat Loss variation from work piece Surface for different Rotational Speed and Transverse Speed

Figure 7 illustrates the convective and radiative heat loss from the work specimen surface apart from the bottom. It has been observed that convective and radiative loss corresponding increases as the rotational speed increases. It has been seen that the rate of heat loss 112.076% increases as the rotational speed 40%. Similarly, when rotational is further increased by 42.86%, the rate of heat loss deduce by 16.29% at 1000rpm.

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Figure 7 also demonstrates the effect of increase in transverse speed on the heat loss (convective and radiative) apart from the bottom. It can be concluded that on increasing transverse speed the rate of convective and radiative heat loss drastically decreases. I.e. on increasing 67% transverse speed from initial, 79.5% decline in heat loss has been scrutinized at 50mm/min.

From this it can be revealed that rotational speed and transverse speed are strong function of heat generation in addition to heat loss.

VI. CONCLUSION

- The obtained results are compared with experimental result and show good agreement and are within acceptable limit.
- The peak temperature at the process zone increases significantly as rotational speed increases. While the weld flash instantaneous becomes further noticeable.
- The peak temperature of work specimen decreases as transverse speed increases.
- The stirring effect of the welding tool radically increases as the weld speed decrease, which in turn improves the weld quality.
- The obtained results show that the heat generated during the FSW process strongly depends upon the transverse speed and the rotational speed.
- At high weld speed and rotational speed must be increased simultaneously in order to avoid from weld defects such as voids.
- From the literature, it has found that residual stress increases simultaneously as rotational and transverse speed increases.
- During Friction stir processing Flash is produced due to material particles on the top surface do not enter the wake and just pile up as the border of the wake at the retreating side of the work piece.
- Throughout welding process increases in temperature extensively effect on grain structure of the weld work piece.
- The heat loss from the bottom surface is monotonous at high rotational speed while, for transverse speed it is remarkable at lower speed.
- Convective and radiative heat loss to the ambient of all the work piece except from the bottom is increasing as the rotational speed increases. Whereas, it decreases as transverse speed increases.

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