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FEA ANALYSIS OF FRICTIONAL HEATING PROCESS (FRICTION HEAT VS. LINEAR VELOCITY)

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ABSTRACT

In the present model only heat generation due to friction is considered. Three-dimensional nonlinear thermal numerical simulations are conducted for the friction stir welding (FSW) of 304L material.Friction stir welding – FSW was a promising welding technology because of its easy use, low energy costs, being ecology friendly process and with no need for filler metal. The aim of the study is to find the heat generated during frictional process. It will help to find trend for the relationship between rotation speed of the tool, translational velocity of tool and the maximum temperature of the welding process. The aim is to create a simple, fast and accurate friction simulation model without the need of complex computational power or knowledge of precise process data.

INTRODUCTION

The objective is to study the effect of tool rotation speed and the maximum temperature developed during the welding process. So it is important to study effect of variation of tool rotational speed and feed rate on the friction. In order to achieve good quality welds, weld input parameters such as tool rotational speed, translation velocity, heat input and tool dimensions have to be properly controlled. As the quality of a weld joint is directly influenced by the input parameters, the welding process can be consider as a multi-input, multi-output process. Thus appropriate combinations of weld parameters have to be chosen to produce high quality welds with minimum detrimental residual stresses and distortions. This study focuses on investigation of input parameters that control the welding temperature in 304L stainless steel friction stir welds. The main objective of the study is to study the effects of tool rotation speed and tool translational velocity on weld heat generated of the developed model.

REVIEW OF MATHEMATICAL MODEL

Procedure For Measurement Of Temperature

The welds of the 304L plates were made in a single pass. The temperature history is recorded during the FSW process by 36 gauge K type thermocouples at nine locations on the top and bottom surfaces along the transverse sections near the middle of the plate. The locations of these points in the workpiece for the case having rotational speed of 300 rpm are shown in Fig. 1. The top row has five thermocouples located at 15, 18, 21, 23.5 and 26.5 mm, respectively. The bottom row is on the back of the plate, and has four thermocouples located at 12.7, 18, 21, and 27.5 mm, respectively. The locations of the thermocouples for the 500 rpm case are only slightly different from those shown in Fig. 1

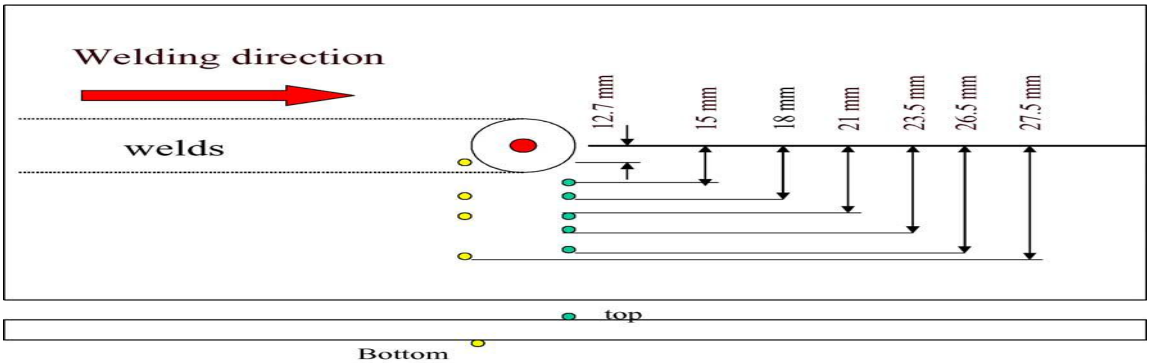


Figure 1 Location of thermocouples in friction stir welding (for the case of 300 rpm tool rotational speed).

Modeling of Friction Stir Welding Process

Friction Stir Welding was invented and experimented at The Welding Institute, UK in 1991. Since then, several experimental methods, numerical/analytical and finite element methods have been developed and studied by many researchers to understand the thermal and thermomechanical interactions taking place during FSW. Despite significant advances in the FSW process, the complex thermomechanical interactions taking place have not been fully understood. In order to predict the Maximum Temperature developed during friction stir welding, thermomechanical models are studied. In most cases, decoupled analysis was used to estimate the residual stresses. In a decoupled analysis, first pure thermal problem is solved and then the calculated temperature fields are used as input to the mechanical models.

Thermal Modeling

Understanding the heat generation and the temperature history during the FSW process is the first step towards understanding the thermomechanical interaction taking place during the welding process. The initial modeling approaches focused on approximate estimation of heat generated during the FSW process. Gould and Feng [1] developed a preliminary thermal model to predict the temperatures of friction stir welds using the Rosenthal equations to describe a moving heat source. The heat input was described as a function of process parameters such as tool rpm and force on tool.

Chao, Qi and Tang [2] formulated a boundary value problem for tool and workpiece in order to study the heat transfer in friction stir welding. They determined the frictional heat flux from the measured transient temperature fields obtained in the finite element analyses. In an attempt to predict the flow of material around the tool, Colegrove et al. [3] presented a finite element based thermal model of FSW. Their model included the backing plate and the tool. In their work, the heat input was fitted through iterative process for verification between the modeled and experimental values.

The above mentioned models did not include the tool penetration and pulling out phase. Song and Kovacevic [4] proposed a coupled heat transfer model of both the tool and the workpiece for FSW to include the tool penetration and pulling out phase. A moving coordinate was adopted to reduce the difficulty of modeling the heat generation due to the movement of the tool pin. The finite difference method was used for solving the control equations and the results obtained were in good agreement with the experimental results.

Vilaca et al. [5] developed an analytical thermal model for simulation of friction stir welding process. The model included simulation of the asymmetric heat field under the tool shoulder resulting from viscous and interfacial friction dissipation. The analytical model also considered the influence of hot and cold FSW conditions into the heat flow around the tool.

Thermomechanical Modeling

In order to estimate maximum temperature and frictional heat resulting from welding process, thermo-mechanical models were developed and studied. One of the first thermo-mechanical models for FSW was studied by Chao and Qi [6]. A decoupled heat transfer and a subsequent thermo-mechanical analysis for Al 6061-T6 was used in their study. Heat generated from friction between tool shoulder and workpiece was implemented as the heat input. The empirical equation
for calculating the heat input to the workpiece is given by equation 1

$$q(r) = \frac{3Qr}{2\pi(r_o^3 - r_i^3)} \qquad \text{for } r_i \leq r \leq r_o \qquad \ldots\ldots\ldots\ldots\ (1)$$

Where
q(r) is rate of heat input
r_i is radius of shoulder of Pin tool
r_o is radius of nib of Pin tool

and Q is the total rate of heat input to the workpiece expressed as shown in equation (2).

$$Q = \frac{\pi\omega\mu F(r_o^2 + r_o r_i + r_i^2)}{45(r_o + r_i)} \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

where, ω is the tool rotational speed, μ is the frictional coefficient, and F is the downward force. The total heat

input and heat transfer coefficient were estimated by fitting the measured temperature data with the analytical model by a trial and error approach. The temperatures thus obtained from the analysis were used.

Chen and Kovacevic [7] proposed a three dimensional finite element analysis model to study the thermal history and thermomechanical process in butt welding of aluminum alloy 6061-T6. The model incorporated the mechanical reaction of the tool and thermomechanical processes of the welded material. The friction between the material, the probe and the shoulder was included in the heat source. X-ray diffraction technique was used to measure the residual stresses developed in the plate and the measured results were used to validate the efficiency of the proposed model. From the study, it was reported that fixturing release to the welded plates affected the stress distribution of the weld.

Zhu and Chao [8] presented three-dimensional nonlinear thermal and thermo-mechanical simulations using finite element analysis code –WELDSIM on 304L stainless steel friction stir welded plates. Initially, a heat transfer problem was formulated as a standard boundary value problem and was solved using the inverse analysis approach. The total heat input and heat transfer coefficient were estimated by fitting the measured temperature data with the analytical model. Later, the transient temperature outputs from the first stage were used to determine residual stresses in the welded plates using a three-dimensional elastic plastic thermo-mechanical model. Convection and radiation were assumed to be responsible for heat loss to the ambient on the surface. Their model provided good match between experimental and predicted results. They reported that the residual stress in the welds after fixture release decreased significantly as compared to those before fixture release. They also reported that about 50% of the total mechanical energy developed by FSW machine was utilized in raising the temperature of the workpiece.

Feng et al. [9] presented a more detailed thermal-metallurgical-mechanical model to study the microstructure changes and their effects on residual stress distribution in friction stir weld of Al6061-T6. In their approach, the first stage involved a transient nonlinear heat flow analysis to determine the temperature distribution. The frictional heating in the thin layer near the interface was treated as surface heat generation term, q, which was estimated by equation 3

$$q = \frac{2\eta\mu F\omega}{60(R_{sh}^2 - R_{pin}^2)} r \qquad \text{for } R_{pin} \le r \le R_{sh} \qquad \ldots\ldots\ldots\ldots(3)$$

where

F is the downward force

ω is the rotational speed

η is the process efficiency

μ is the interpretive coefficient of friction

Rpin and Rsh the radii of the pin and the shoulder respectively

In the second stage, using the temperature history from the thermal model as input, the metallurgical calculations were performed in the mechanical analysis as a part of material constitutive definition subroutine. It was reported that residual stresses had strong dependence on the welding speed.

Li et al. [10] presented a semi coupled thermo mechanical finite element model containing both thermal load and mechanical load. Their model included an auto adapting heat source in the thermal model and fixtures were included in the mechanical model. They reported that in the case of 2024-T6 alloy, stresses at the retreating side of the weld were smaller than those at the advancing side.

Staron et al. [11] conducted experimental study on residual stress states in FSW joints in 6.3 and 3.2 mm thick AA2024 sheets that had been welded under mechanical tensioning. They were successful in reducing the tensile residual stress in the weld zone by induction of large compressive stresses through mechanical tensioning.

Dattoma et al. [12] evaluated the residual stress fields in similar and dissimilar joints in 2024-T3 and 6082-T6 Aluminium alloy using hole-drill method. Findings from their study showed that in thicker joints very high longitudinal stresses were present and adequate shoulder geometries resulted in reduction of residual stress values.

RESULTS AND DISCUSSION

First analysis with 60 rpm and 2.71 mm/s tool velocity

The objective of the project is to find Maximum Temperature and Frictional Heat generated during welding process. The main FSW process parameters that affect both the weld quality and the process efficiency are: (a) rotational and transverse velocities of the tool; (b) tool plunge depth; (c) tool tilt angle; and (d) tool design/material. Since, in general, higher temperatures are encountered in the case of higher rotational and lower transverse tool velocities, it is critical that a delicate balance between these two velocities is attained: i.e. when the temperatures are not high enough and the material has not been sufficiently softened, the weld zone may develop various flaws/ defects arising from low ductility of the material.

Conversely, when the temperatures are too high undesirable changes in the material microstructure/ properties may take place and possibly incipient melting flaws may be created during joining. Initially the Rotation of the tool is considered as 60 RPM and tool feed rate is 2.71 mm/s Total Time steps = 29, There are total 3 steps in FSW process. Time require for each step is calculated

Load step 1:

Tool is drilled into the workpiece. To ensure that the necessary level of shoulder/workpiece contact pressure is attained and that the tool fully penetrates the weld, the tool plunge depth (defined as the depth of the lowest point of the shoulder below the surface of the welded plate) has to be set correctly. Typically, insufficient tool plunge depths result in low-quality welds (due to inadequate forging of the material at the rear of the tool), while excessive tool plunge depths lead to undermatching of the weld thickness compared to the base material thickness. Depth of penetration is = thickness of plate/4000= 3.18/4000 mm, Time required for step 1 = 1sec.

Load step 2:
Tool is rotated at given RPM, in this case it is 60RPM. Time Required for step 2: 6.5 sec.

Load step 3:
Feed length= 60.96 mm, Total time = 22.5 sec, Tool feed rate= 2.71 mm/s. Tool is translated along the weld line with 2.71 mm/s feed rate and the rotation of tool is 60 rpm. Lower the tool feed rate, better the quality of weld.

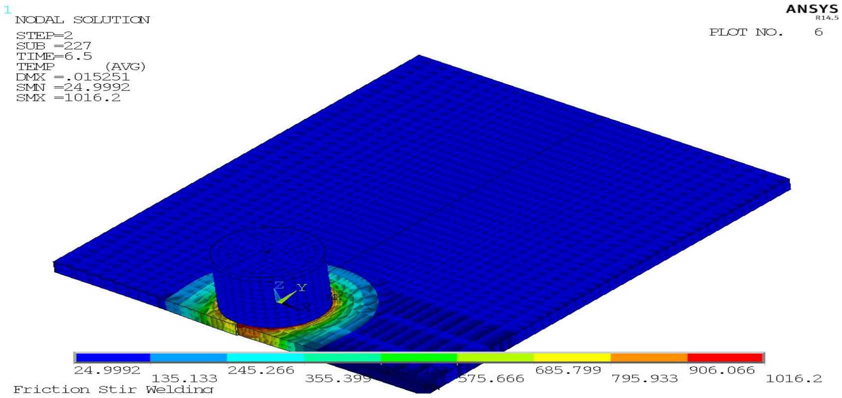


Figure 2 Temperature after Load step 2

Figure 2 and 3 shows the effect of Rotation and translation velocity on the workpiece. Initially when too start rotating for 5.5 sec. the workpiece temperature is raise to 1016.2ºC. As the tool complete load step 3, the temperature of workpiece is 1109.04ºC.

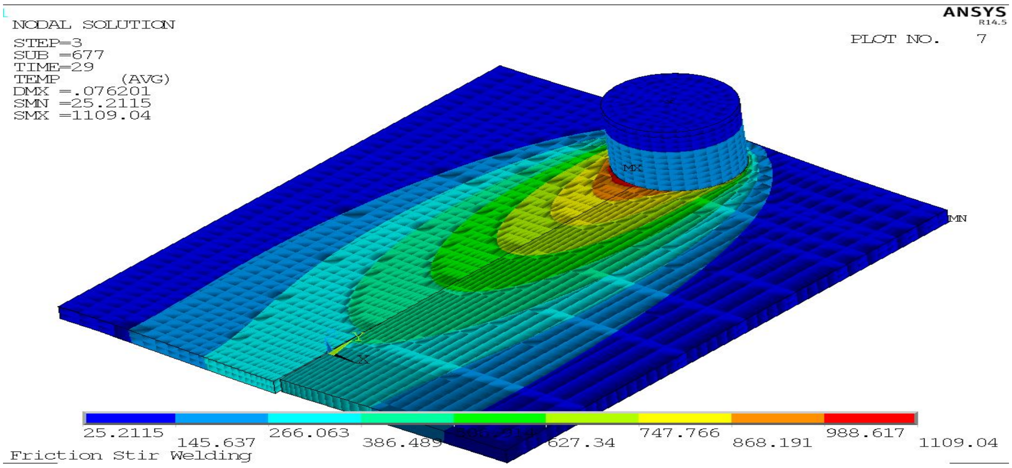
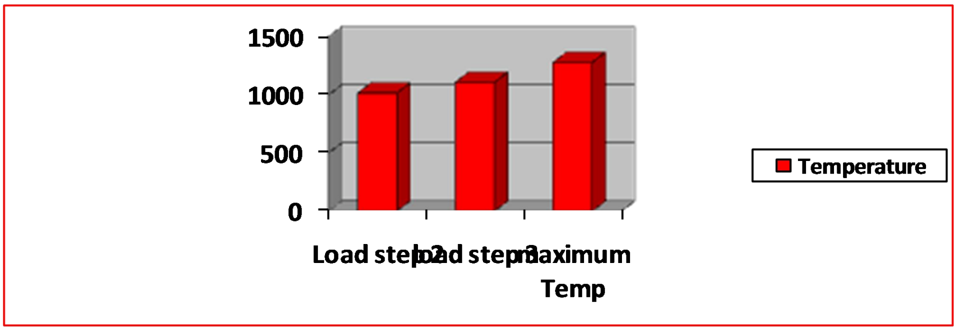
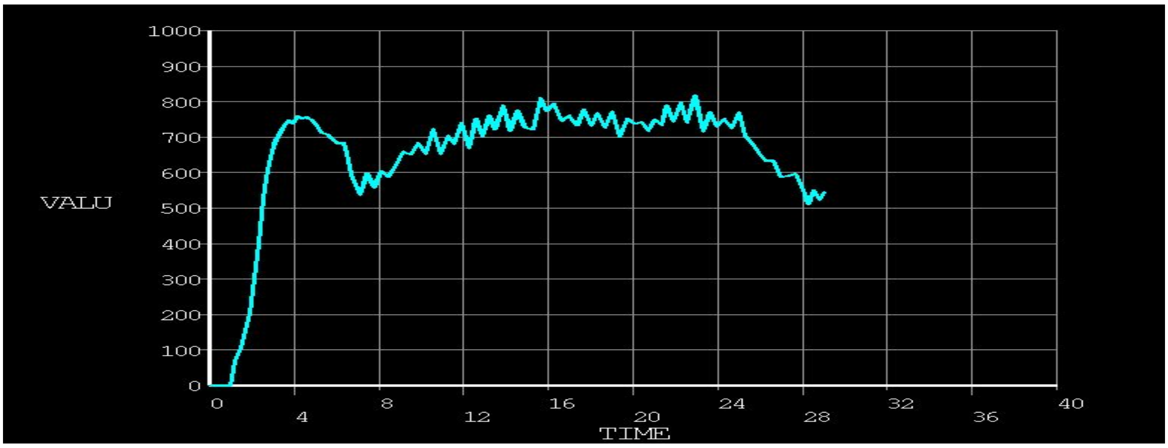


Figure 3 Temperature after Load step 3

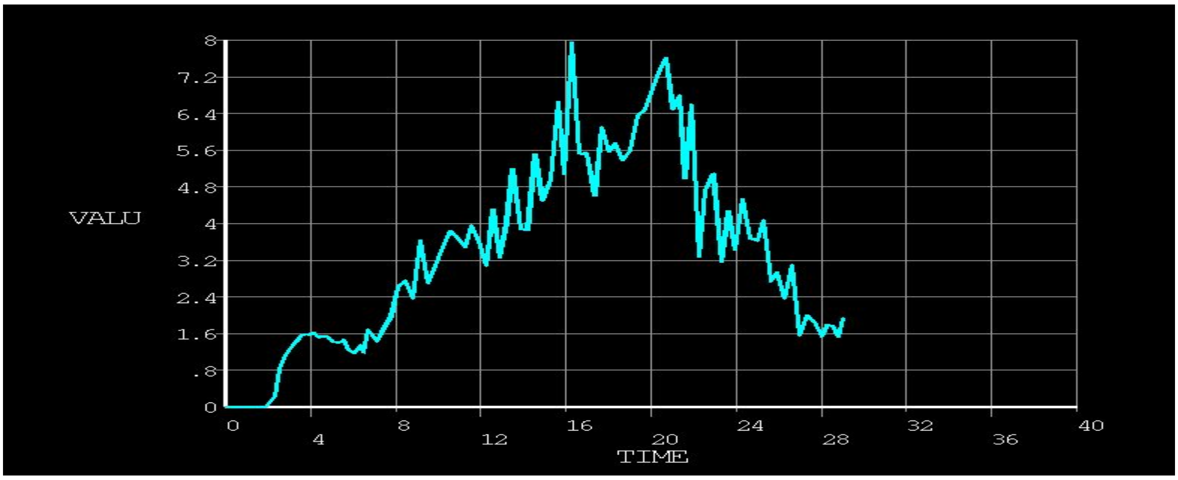


Graph 1 Temperature at various load step vs. max. Temperature

Graph 1 shows the change of temperature with respect to load steps. From this graph it is clear that the process reaches maximum temperature between the load step 2 and 3. . temperature generated due to friction is about 820ºC. (Graph 2)



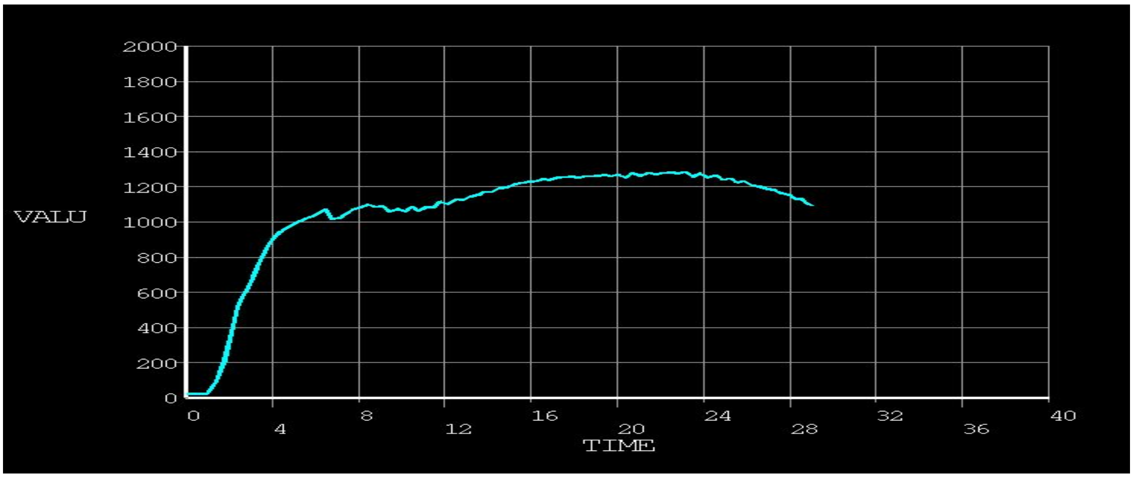
Graph 2 Friction Heat vs. Time graph.



Graph 3 Plastic heat rate against time graph

Graph 3 indicates maximum plastic heat rate is 8 and it is obtain after 16 seconds.

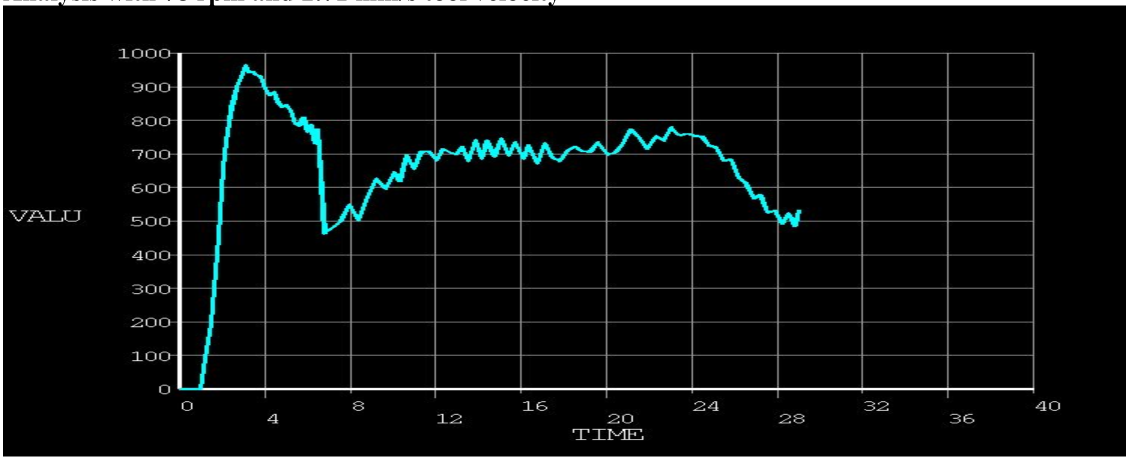
Analysis with 66 rpm and 2.71 mm/s tool velocity



Graph 4 Friction Heat vs. Time graph.

Fiction heat is increases with time but is will slightly decreases at the end of the process.

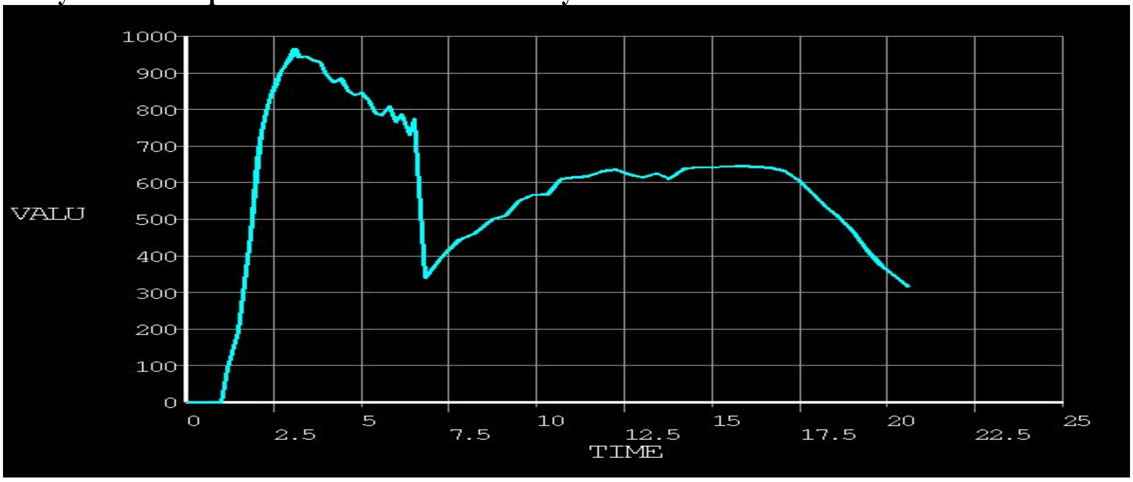
Analysis with 78 rpm and 2.71 mm/s tool velocity



Graph 5 Friction Heat vs. Time graph.

Maximum friction heat develop is between 900 to 1000 J.

Analysis with 78 rpm and 4.328 mm/s tool velocity



Graph 6 Friction Heat vs. Time graph.

The friction heat suddenly increases after 3 seconds. Then it decreases.

Tables of input parameters (The value of rotation and velocity is increased by 10%. See table no 1)

I. Various parameters at 60 rpm.

Table 1 Rotation speed and Time at 60 rpm

Sr. No.	Velocity(mm/s)	Rotational speed for load step 2 (rpm)	Rotational speed for load step 3 (rpm)	Time for load step 3 (Sec)
1	2.71	60	60	22.5
2	2.981	60	60	20.45
3	3.252	60	60	18.745
4	3.577	60	60	17.039
5	3.935	60	60	15.492
6	4.328	60	60	14.084

II. Various parameters at 66 rpm.

Table 2 Rotation speed and Time at 66 rpm

Sr. No.	Velocity(mm/s)	Rotational speed for load step 2 (rpm)	Rotational speed for load step 3 (rpm)	Time for load step 3 (Sec)
1	2.71	66	66	22.5
2	2.981	66	66	20.45
3	3.252	66	66	18.745
4	3.577	66	66	17.039
5	3.935	66	66	15.492
6	4.328	66	66	14.084

III. Various parameters at 72 rpm.

Table 3 Rotation speed and Time at 72 rpm

Sr. No.	Velocity(mm/s)	Rotational speed for load step 2 (rpm)	Rotational speed for load step 3 (rpm)	Time for load step 3 (Sec)
1	2.71	72	72	22.5
2	2.981	72	72	20.45
3	3.252	72	72	18.745
4	3.577	72	72	17.039
5	3.935	72	72	15.492
6	4.328	72	72	14.084

IV. Various parameters at 78 rpm.

Table 4 Rotation speed and Time at 78 rpm

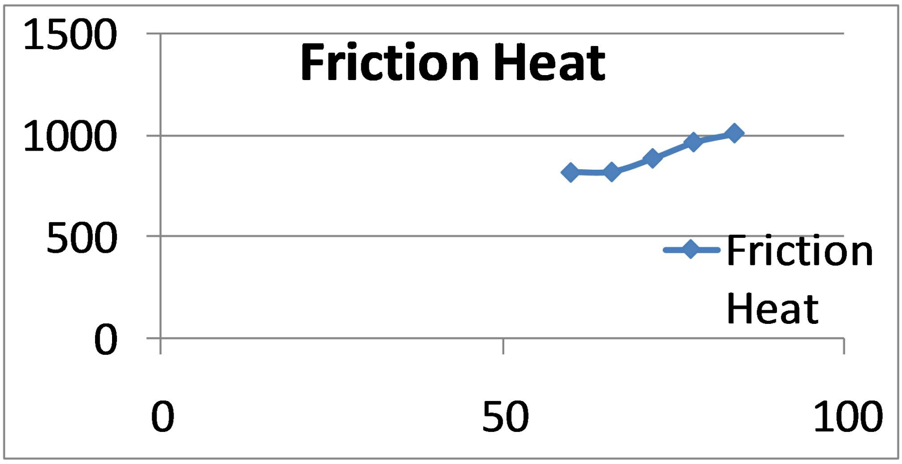
Sr. No.	Velocity(mm/s)	Rotational speed for load step 2 (rpm)	Rotational speed for load step 3 (rpm)	Time for load step 3 (Sec)
1	2.71	78	78	22.5
2	2.981	78	78	20.45
3	3.252	78	78	18.745
4	3.577	78	78	17.039
5	3.935	78	78	15.492
6	4.328	78	78	14.084

V. Various parameters at 84 rpm.

Table 5 Rotation speed and Time at 84 rpm

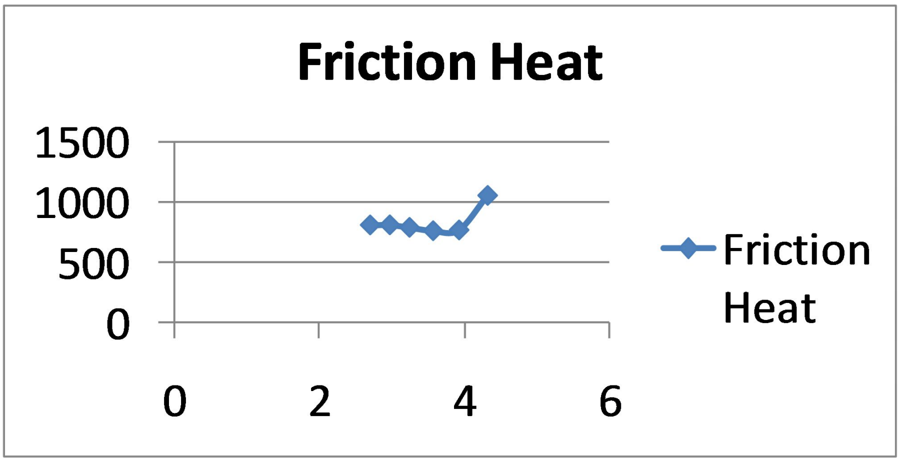
Sr. No.	Velocity(mm/s)	Rotational speed for load step 2 (rpm)	Rotational speed for load step 3 (rpm)	Time for load step 3 (Sec)
1	2.71	84	84	22.5
2	2.981	84	84	20.45
3	3.252	84	84	18.745
4	3.577	84	84	17.039
5	3.935	84	84	15.492
6	4.328	84	84	14.084

Graphs



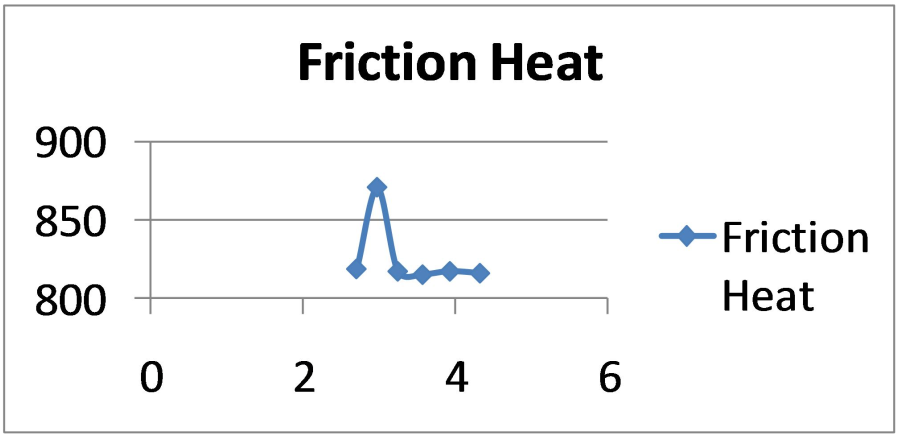
Graph 7 Frictional heat vs rotational speed

Graph 7 indicates change of friction heat with respect to rotation speed. The friction heat increases linearly with respect to rotation speed.



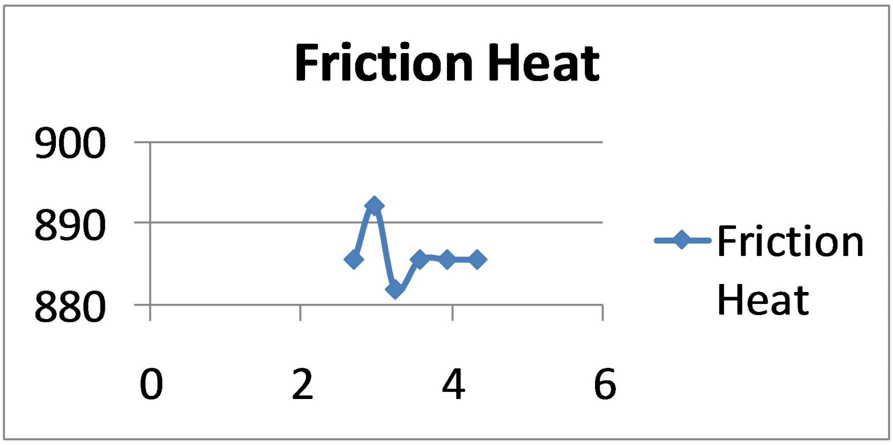
Graph 8 Friction Heat vs velocity (rotational speed 60 rpm)

friction decrease with increase in tool velocity. But at 4.328 mm/s velocity increases suddenly as indicated by graphs.



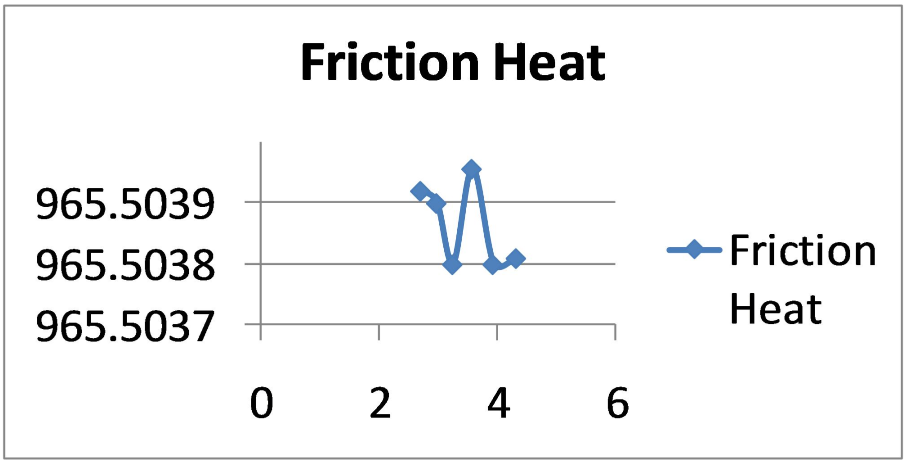
Graph 9 Friction Heat vs velocity (rotational speed 66 rpm)

The friction heat suddenly increases for 2.981 mm/s tool velocity but for remaining tool velocities friction heat remains constant.



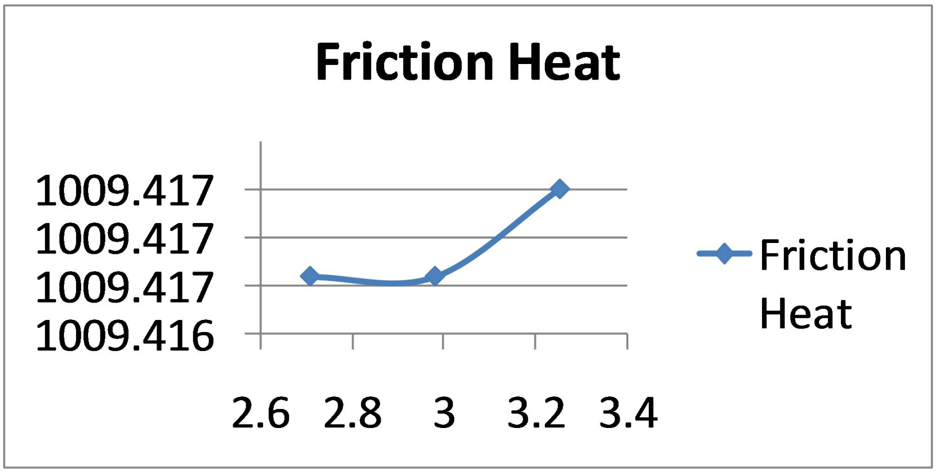
Graph 10 Friction Heat vs velocity (rotational speed 72 rpm)

At 72 rpm the variation in frictional heat is very less.



Graph 11 Friction Heat vs velocity (rotational speed 78 rpm)

The friction heat is also constant at 78 rpm for all tool velocities and the value of friction heat is 965.5 J.



Graph 12 Friction Heat vs velocity (rotational speed 84 rpm)

CONCLUSION

- To find temperature and frictional heat in welding process non-linear Thermo-coupled analysis is used.
- It is observed that tool rotation speed and tool velocity plays an important role in friction stir welding process.
- Following are the trends seen in the FSW analysis are given below;
    1. As the rotation speed Increases the friction heat developed also increases between tool and the workpiece.
    2. At higher tool rotation speed the frictional heat is constant and is independent of tool linear velocity.
    3. There is decreased in friction heat at lower tool rotation speed and increased in tool velocity
    4. For better weld we suggest higher tool rotation speed and lower tool velocity.

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