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FEA ANALYSIS OF FRICTIONAL HEATING PROCESS (MAX. TEMPERATURE VS. ROTATIONAL SPEED)

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ABSTRACT
Friction stir welding process is a promising welding technology from its existence as it is easy to use, low energy costs, being ecology friendly process and with no requirement of any type of filler material. This study of FSW gives analysis of the maximum temperature generated during operation. This is done by making three dimensional non-linear model. This model helps in trend for the relationship between translational velocity of tool, rotation speed of the tool, and the maximum temperature of the FSW 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.

KEYWORDS: Friction stir welding, Thermomechanical, rotational speed, Translational velocity, Finite element analysis.

INTRODUCTION
Friction Stir Welding (FSW) is a revolutionary solid state welding technique invented at The Welding Institute (TWI) in 1991 [1]. The FSW process operates below the solidus temperature of the metals being joined and hence no melting takes place during the process. This process is a derivative of the conventional friction welding and is being used to produce continuous welded seams for plate fabrication [2]. Since its invention in 1991, continuous attempts have been made by researchers to understand, use and improve this process.

PROCESS
Friction stir welding (FSW) is a solid–state, hot–shear joining process [1–3] in which a rotating tool with a shoulder and terminating in a threaded pin, moves along the butting surfaces of two rigidly clamped plates placed on a backing plate as shown in Fig. 1. The shoulder makes firm contact with the top surface of the work–piece. Heat generated by friction at the shoulder and to a lesser extent at the pin surface, softens the material being welded. Severe plastic deformation and flow of this plasticised metal occurs as the tool is translated along the welding direction. Material is transported from the front of the tool to the trailing edge where it is forged into a joint. Although Fig. 1 shows a butt joint for illustration, other types of joints such as lap joints and fillet joints can also be fabricated by FSW.

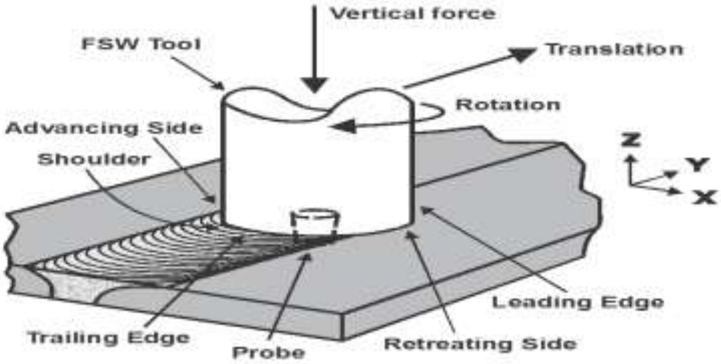

Figure 1 Friction stir welding process

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THERMOMECHANICAL MODEL FOR FSW

Model Development of Friction Stir Welding for 304L Stainless Steel

The ANSYS® program has many finite element analysis capabilities, ranging from simple, linear, static analysis to a complex nonlinear, transient dynamic analysis. The thermal and mechanical responses of the material during friction stir welding process are investigated by finite element simulations. In this study, a sequentially coupled thermo-mechanical model is developed for analysis. First, a nonlinear, transient three-dimensional heat transfer model is developed to determine the temperature fields. Later, the temperature fields are used as input for a nonlinear, rate independent, three-dimensional structural model in order to predict the distortions and the residual stresses. The finite element models are parametrically built using APDL (ANSYS Parametric Design Language) provided by ANSYS®. The models are then validated by comparing the results with experimental data.

Thermal Model

The purpose of the thermal model is to calculate the transient temperature fields developed in the workpiece during friction stir welding. In the thermal analysis, the transient temperature field T which is a function of time t and the spatial coordinates (x,y,z), is estimated by the three dimensional nonlinear heat transfer equation (1).

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q_{int}=c\rho\frac{\partial T}{\partial t} \quad \text{……………………(.1)}$$

Where

k is the coefficient of thermal conductivity

Qint is the internal heat source rate

c is the mass-specific heat capacity

ρ is the density of materials [28]

The heat transfer model developed for the thermal analysis is described in the following section.

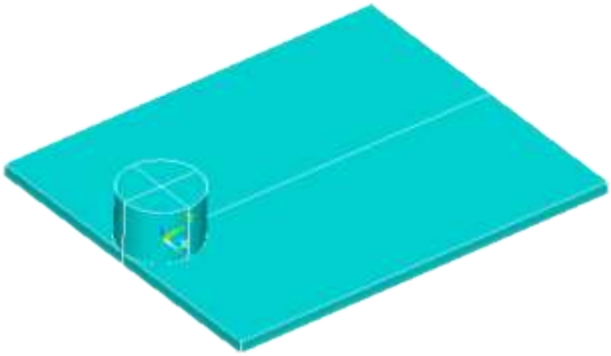
Assumptions

A number of assumptions have been made in developing the finite element thermal model, which include:

- Workpiece material is isotropic and homogeneous.
- No melting occurs during the welding process.
- Thermal boundary conditions are symmetrical across the weld centreline.
- Heat transfer from the workpiece to the clamp is negligible.

Geometry

In the numerical model, only half of the welded plate is modeled as the weld line is the symmetric line. Symmetric condition is used to reduce the simulation time. The workpiece has dimensions of 0.0762 m x 0.03175 m x 0.00318 m.



- l=Length of each plate = 76.2 mm
- w=Width of each plate = 31.75 mm
- t=Tickness of each plate = 3.18 mm
- r1=Shoulder radius of tool = 7.62 mm
- h=Height of tool = 15.24 mm
- l1=r1 Starting location of tool on weldline = 7.62 mm
- l2=l-l1= Tool travel distance

Elements Used

In the present thermal analysis, the workpiece is meshed using a brick element called SOLID 226. SOLID226 has the following capabilities:

- Structural-Thermal

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- Piezoresistive
- Electroelastic
- Piezoelectric
- Thermal-Electric
- Structural-Thermoelectric
- Thermal-Piezoelectric
- Structural-Diffusion
- Thermal-Diffusion
- Structural-Thermal-Diffusion

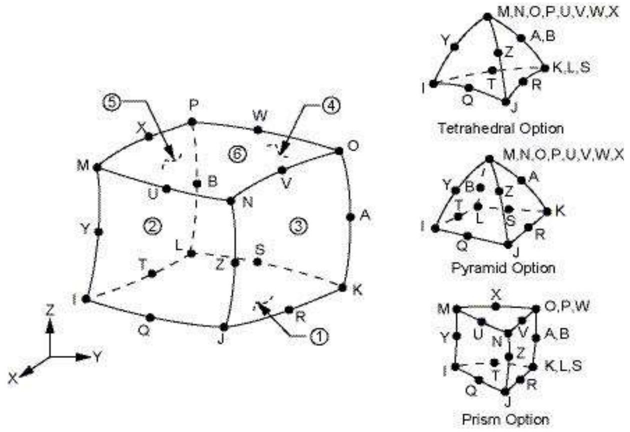

Figure 2 Three dimensional thermal solid element SOLID 226

As SOLID 226 cannot apply heat flux and convection at the same time, a three-dimensional thermal-surface-effect element was used. For applying convection on the workpiece surface, TARGET 170 was used overlaying it onto faces of the base elements made by SOLID226. The convections were applied as a surface load by choosing KEYOPT (8) >1. Figure 2 shows the geometry, node locations, and the coordinate system of the element, which is defined by four to nine nodes and the material properties.

TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements. The contact elements themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170.

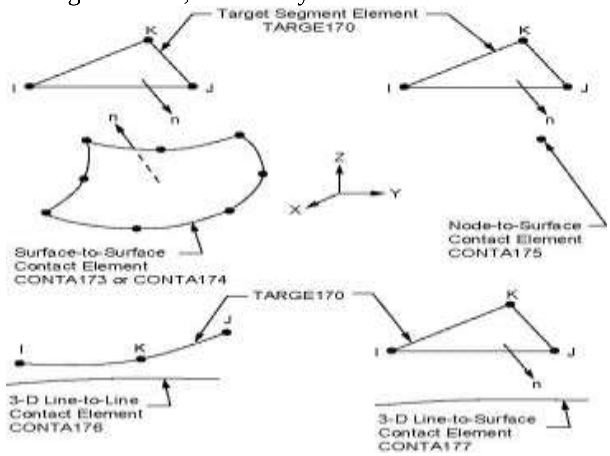

Figure 3 TARGET 170

Mesh Development

Three dimensional SOLID226 elements were used to mesh the sheets. The workpiece was divided into 22 parts along the length with spacing ratio 5, 44 parts along the width and 2 parts along the thickness direction. The mesh is comprised of a total number of 5214 elements and 7879 nodes.

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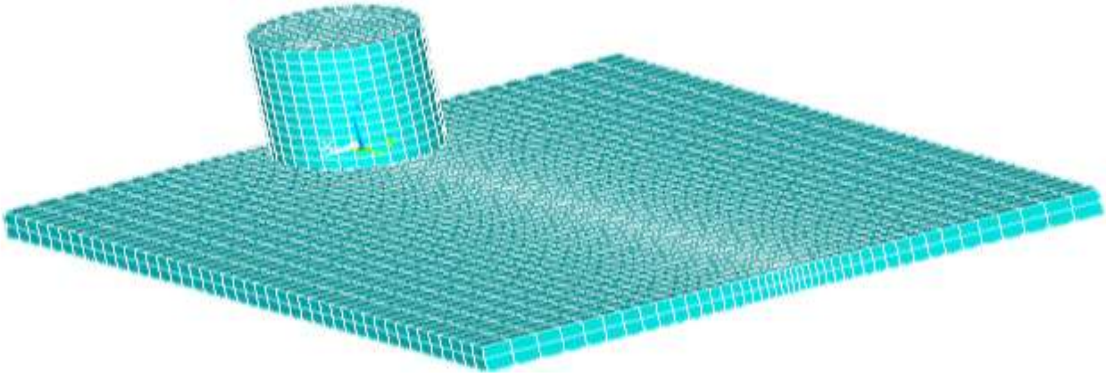

Figure 3 Meshing of model

From figure 3, the meshing is denser along the weld line.

Material Properties

The thermal material properties of 304L stainless steel are tabulated in Table 1.The thermal property values are obtained from [28, 51], and for higher temperatures the values are linearly extrapolated.

- Ex = 193e9 (N/m^2)
- Poisson's ratio = 0.3
- Coefficient of thermal expansion = 1.875e^{-5}
- Fraction of plastic work converted to heat is 80%
- Yield stress= 290e6 (N/m^2)
- tangent modulus= 2.8e9 (N/m^2)

Temperature (℃)	0	200	400	600	800	1000
Specific heat	500	540	560	590	600	610
Thermal Conductivity	16	19	21	24	29	30
Density	7894	7744	7631	7518	7406	7406

Table 1 Thermal material properties of 304L stainless steel

Properties of PCBN (Polycrystalline Cubic Boron Nitride)

- Ex = 680e9 (N/m^2)
- Poisson's ratio = 0.22
- Thermal conductivity=100 (W/m°C)
- Specific heat=750 (J/kg°C)
- Density= 4280 kg/m^3

Coefficient of friction between tool and the workpiece is varies with respect to Temperature. Its values are given in Table 2

Temperature (℃)	0	200	400	600	800	1000
Coefficient of friction	0.4	0.4	0.4	0.3	0.3	0.2

Table 2 Coefficient of Friction

Boundary Condition

Due to the complexity involved in estimating the contact condition between the sheet and the backing plate, the value of β_b had to be estimated by assuming different values through reverse analysis approach. In this study, the optimized value of β_b was found to be 100 W/cm^2℃. Figure 47.7 shows the schematic representation of boundary conditions that were used for thermal analysis

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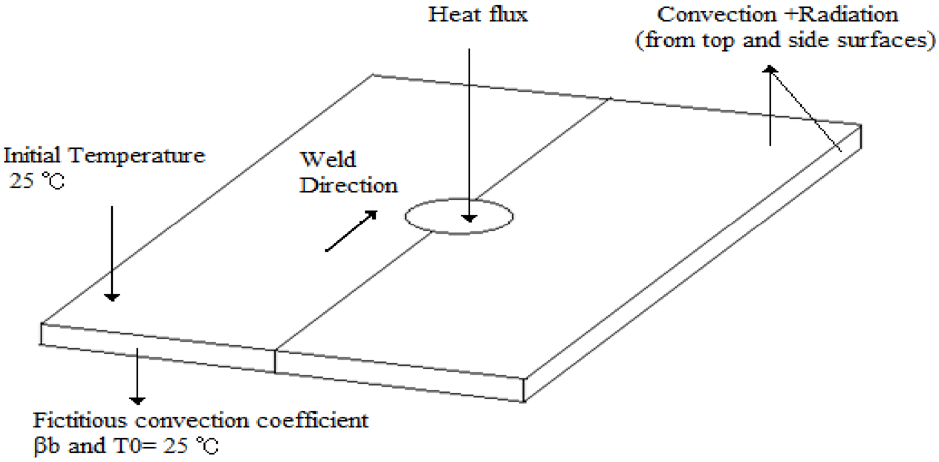

Figure 7.7 Schematic representation of boundary condition for thermal analysis

RESULTS AND DISCUSSION

8.1 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.

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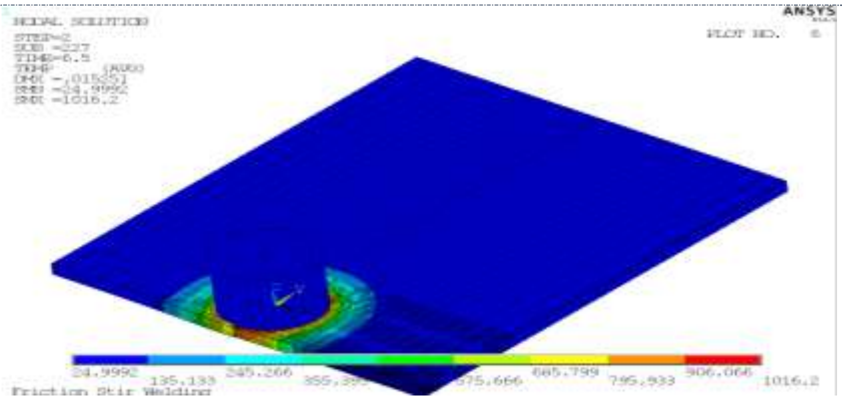


Figure 8.1 Temperature after Load step 2

Figure 8.1 and 8.2 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.

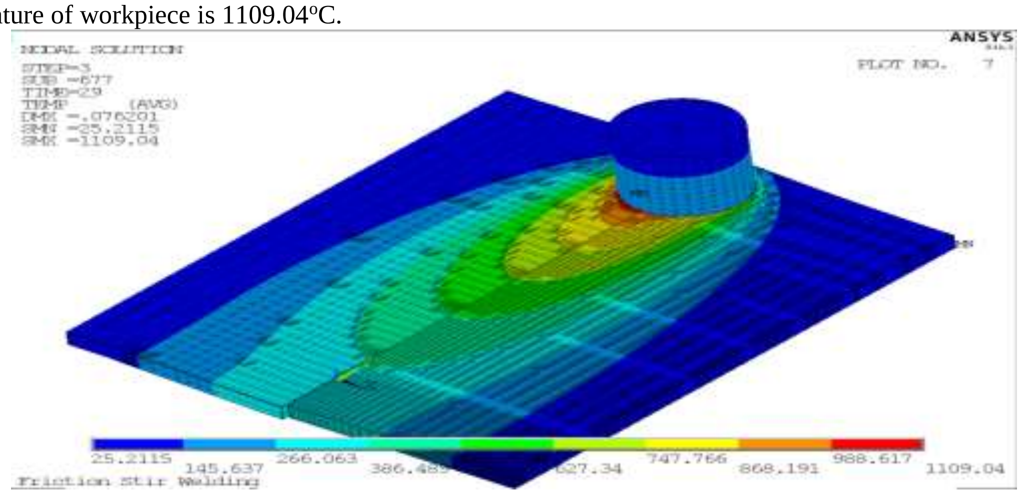
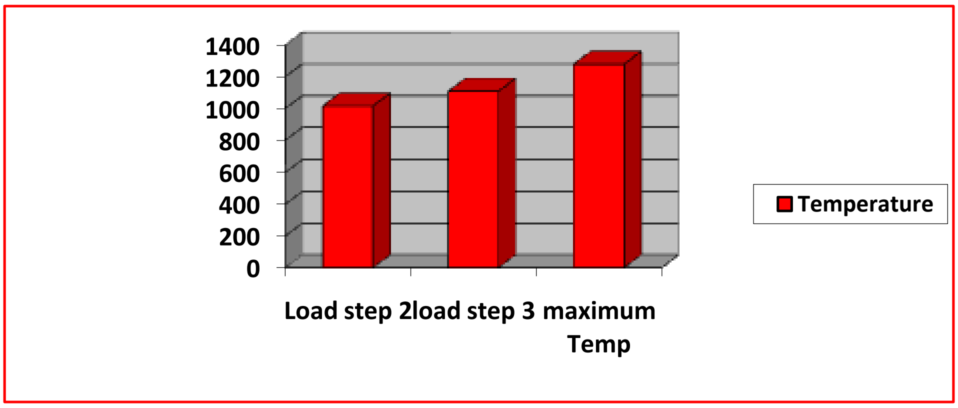
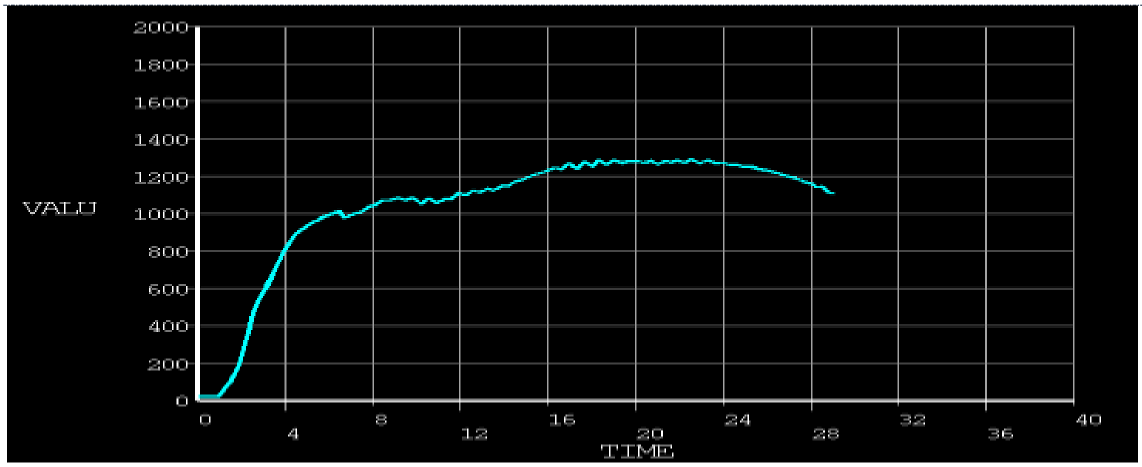


Figure 8.2 Temperature after Load step 3



Graph 8.1 Temperature at various load step vs. max. Temperature

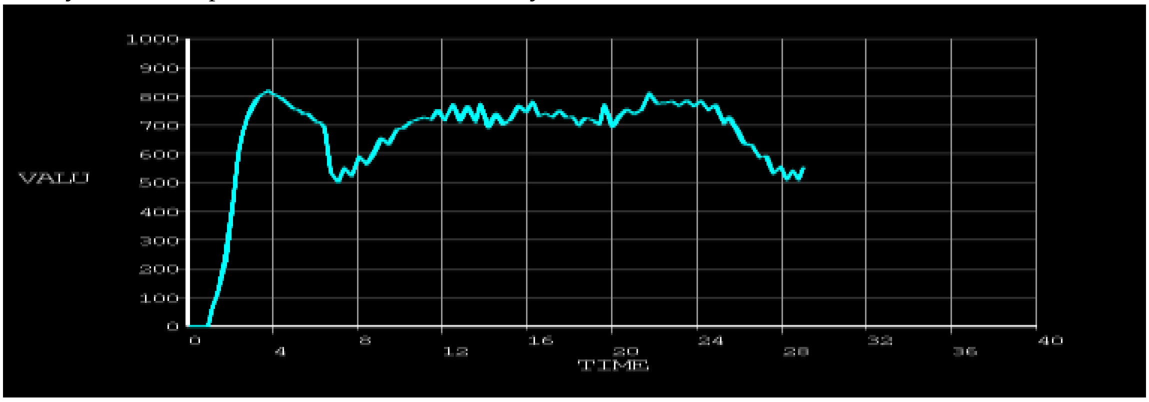
Graph 8.1 shows the change of temperature with respect to load steps. From this graph it is clear that the process reaches maximum temperature between the load step 2 and 3. The temperature vs. time graph is shown below.



Graph 8.2 Temperatures vs. Time

It is observed that temperature slowly increases with time. It reaches maximum temperature at 18 sec after the process started and corresponding temperature is 1300°c.

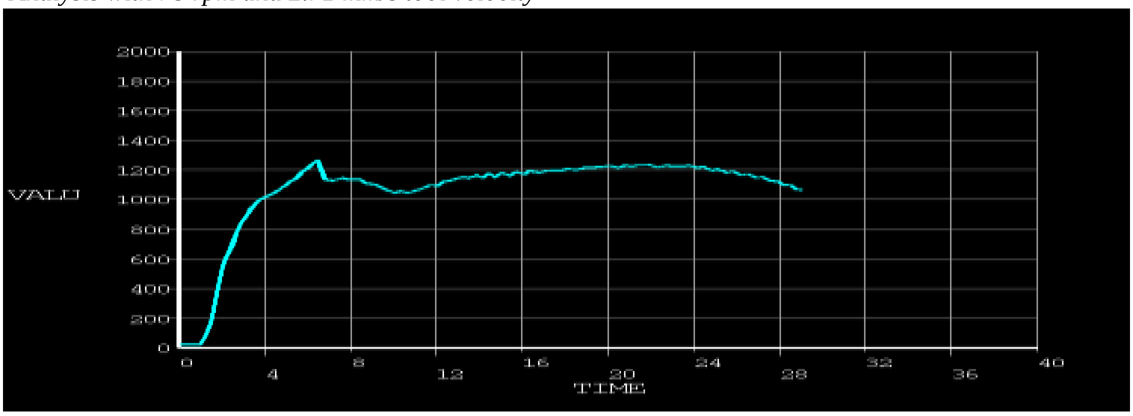
8.2 Analysis with 66 rpm and 2.71 mm/s tool velocity



Graph 8.5 Temperatures vs. Time

The Temperature variations are shown in the graph. For first few seconds the temperature increases linearly, after 4 sec there is sudden decrement in the welding temperature. After 7 seconds temperature rises.

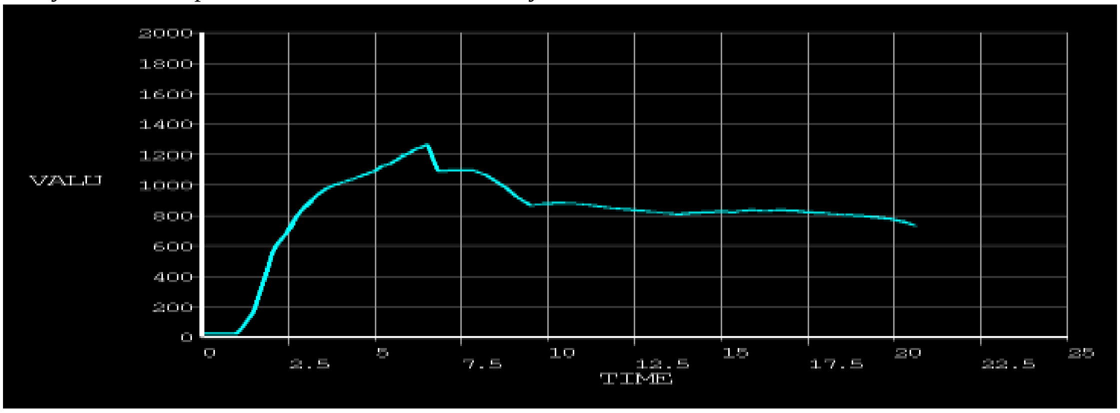
8.3 Analysis with 78 rpm and 2.71 mm/s tool velocity



Graph 8.7 Temperatures vs. Time

For first few seconds temperature increases linearly the there is sudden drop in the temperature. The temperature achieve during initial stage is the maximum temperature.

8.4 Analysis with 78 rpm and 4.328 mm/s tool velocity



Graph 8.9 Temperatures vs. Time

Temperature increases slowly up to 6 sec then it decreases continuously.

*8.5 Tables of input parameters (T*he value of rotation and velocity is increased by 10%. See table no 8.1)

I. Various parameters 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

Table 8.1 Rotation speed and Time at 60 rpm

II. Various parameters 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

Table 8.2 Rotation speed and Time at 66 rpm

III. Various parameters 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

Table 8.3 Rotation speed and Time at 72 rpm

IV. Various parameters at 78 rpm.

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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

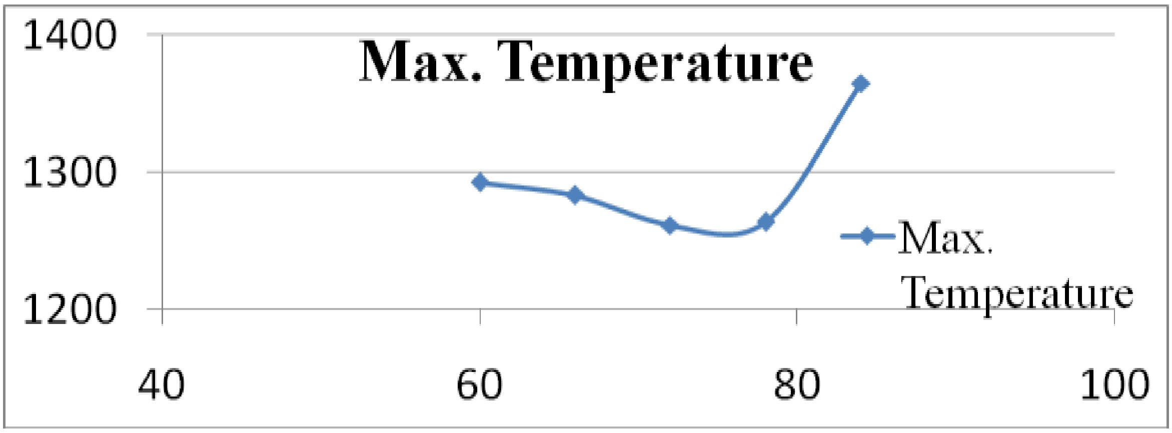
Table 8.4 Rotation speed and Time at 78 rpm

V. Various parameters 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

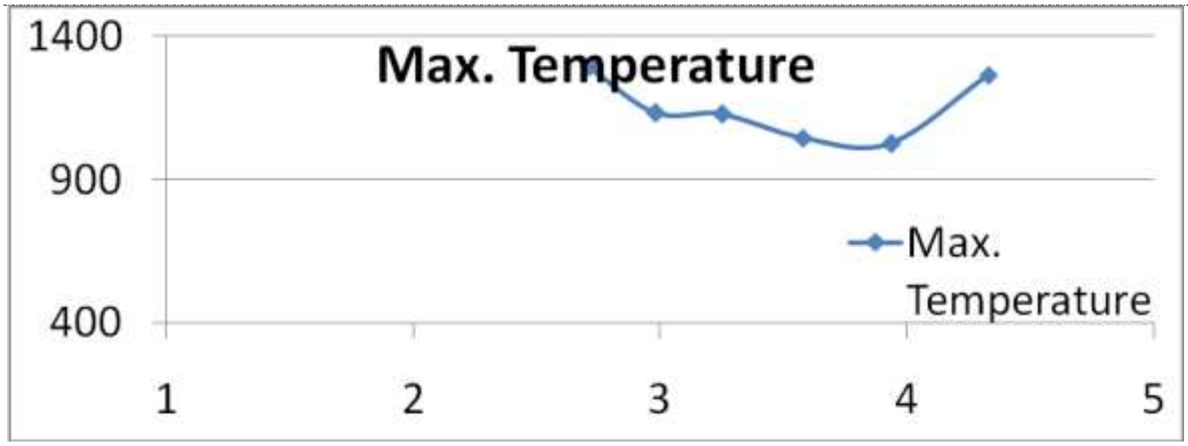
Table 8.5 Rotation speed and Time at 84 rpm

Graphs

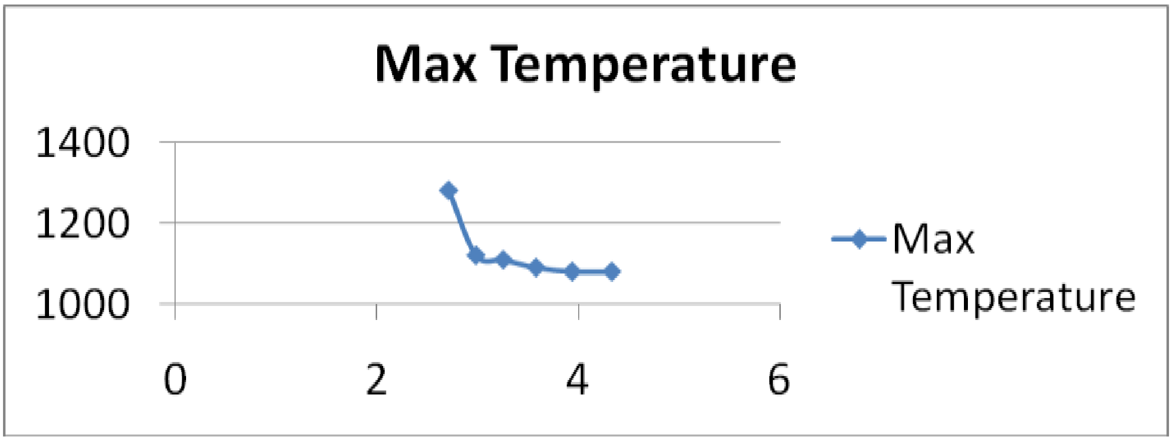


Graph 8.11 Max temperature vs rotational speed

Graph 8.11 indicates change of temperature with respect to rotation speed of welding tool. The maximum temperature decrease after 60 rpm. The temperature is suddenly increase after 78 seconds and reaches its maximum value. Variation of maximum temperature with respect to tool velocity and rotation speed is given into following graph.

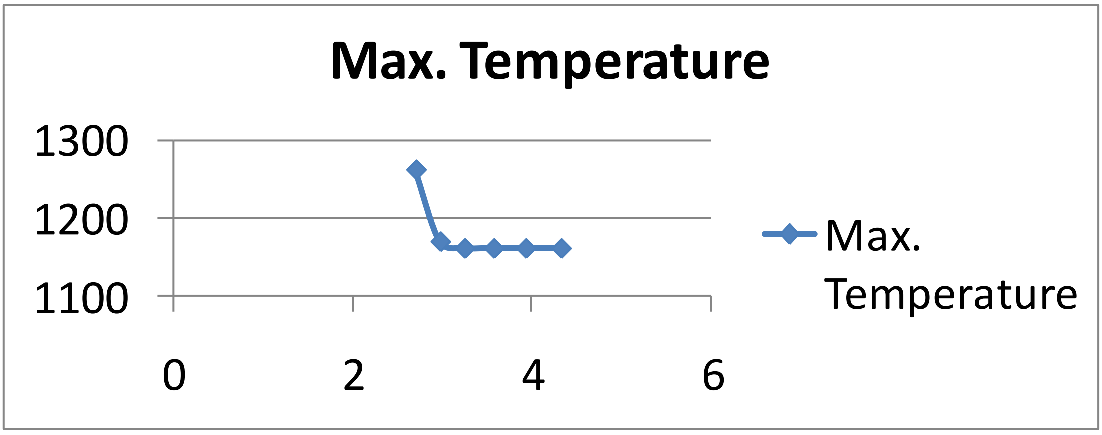


Graph 8.13 Max temperature vs velocity (rotational speed 60 rpm)



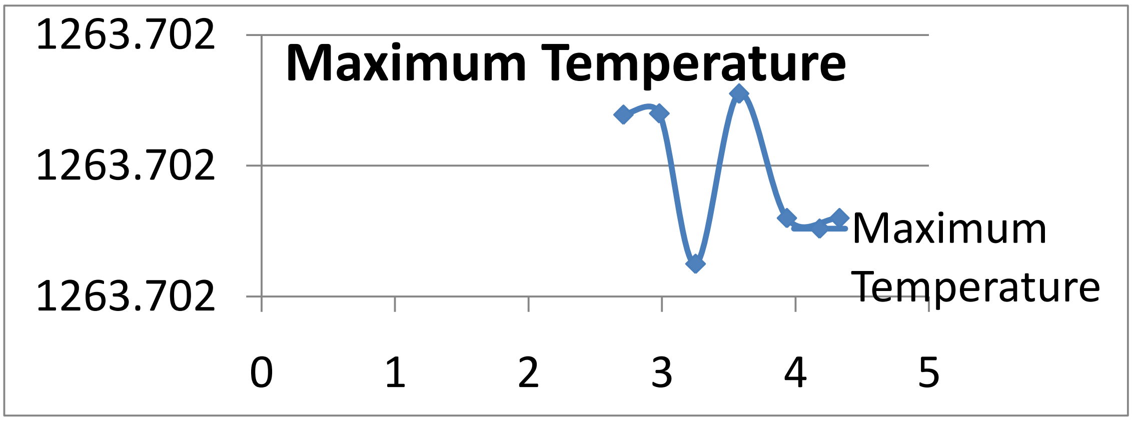
Graph 8.15 Max temperature vs velocity (rotational speed 66 rpm)

The maximum temperature decreases suddenly after the tool velocity increases. At higher velocities the temperature remains constant.



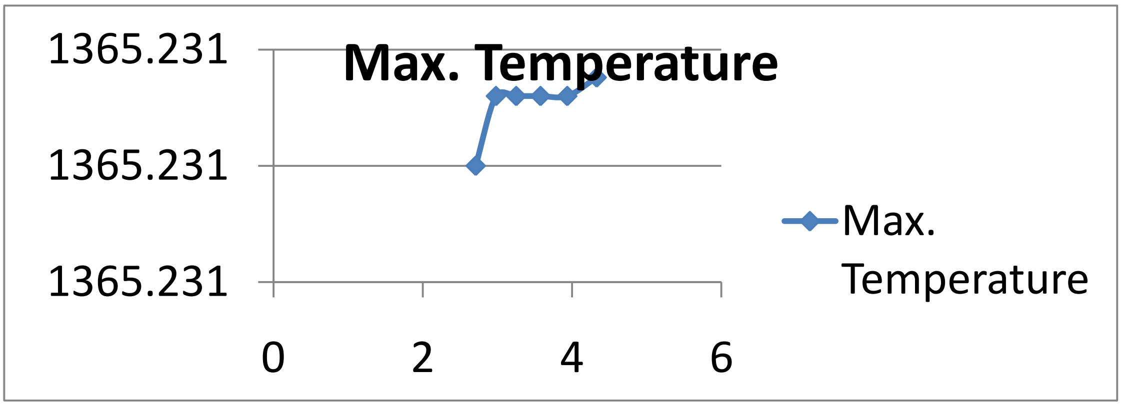
Graph 8.17 Max temperature vs velocity (rotational speed 72 rpm)

At 72 rpm speed the maximum temperature suddenly decreases as the tool velocity increases and then it is value remains constant.



Graph 8.19 Max temperature vs velocity (rotational speed 78 rpm)

The variation in maximum temperature is negligible, so we can say the maximum temperature at this rotation speed is constant for all tool velocities.



Graph 8.21 Max temperature vs velocity (rotational speed 84 rpm)

The variation in maximum temperature is negligible, so we can say the maximum temperature at this rotation speed is constant for all tool velocities.

CONCLUSION

- Non-linear and Thermo-couple analysis is used to find temperature and friction heat in welding operation.
- From that it is concluded that tool rotation speed and tool velocity plays an important role in friction stir welding operation.
- During the process the different trends observe are given below;
  - When the rotational speed of the tool increases, the maximum temperature decrease because of rise in convection.
  - At 84 rpm of the tool rotation, temperature again increases and reaches to the maximum value. This is the maximum temperature that we observed.
  - At 60 rpm of the tool rotation, the effect of velocity is more. As the tool velocity increases it decreases the temperature of welding operation.
  - Variation in maximum temperature observed at higher tool rotation speed because of tool velocity is negligible.
  - Higher tool rotation speed and lower tool velocity suggested for better weld patch.

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