Mathematical Model For Analysis of Heat Transfer In Friction Stir Welding

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Abstract- *In this project firstly we started with the basic study of Friction Stir Welding (FSW) so as to develop the understanding of the welding process along with the principles and process parameters involved in this welding and as this is new technique patented in 1991, so we had a lot to deal with.*

We went through previous literatures and works that have been carried out so as to develop the understanding of Theoretical and Heat Transfer Modelling. We also carried out our study on the different heats generated and heat transfer mechanism in friction stir welding along with the different parameters affecting the heat generation and transfer in FSW. We further went through the different equations of heat transfer that are or can be involved in this welding process and tried to develop a mathematical model of this process considering the material and interface behaviours and friction as well.

Finally transient temperature distribution during FSW of alloy was simulated using finite element modelling. The precise 3D finite element simulation of the Friction Stir Welding (FSW) process needed a proper information of both the materials and interface behaviours, but friction, the key phenomenon of this process is little bit difficult to modelling and identify.

A three dimensional finite element model was developed on ABAQUS, the model was used to predict the peak temperature and analyse the thermal history during FSW.

The model results were validated using the experimental results from the published literature mentioned in the reference [1].

I. INTRODUCTION

Friction stir welding (FSW) is one of the recently developed solid- state joining processes where similar or dissimilar materials such as aluminium, magnesium, and their alloys are joined by plasticization. The process consists of a rotating tool which is plunged into two plates tightly abutted along a line and the line is traversed by the rotating tool. During the process, heat is generated by p.lastic deformation as well as by the friction between the tool and the work piece. The work pieces are ultimately joined by the stirring action of the tool to soften the material with excellent combination of mechanical properties.

This method is often preferred due to low residual stress, low energy input, and fine grain size compared to the conventional fusion welding processes. Hence to knowing of the heat transfer mechanism in the work piece material can be helpful to predict thermo- mechanical interactive phenomena, thermal history during the welding process and the mechanical properties of the weld joint that finally evaluate the weld joint quality. Several researchers have analysed the thermal aspects of FSW and concluded that the estimation of temperature profile intuitively depends on precise consideration of heat source model along with boundary interaction in terms of contact condition.

The solid state behaviour of FSW leads to more advantages over fusion welding technique, as problems associated with cooling from the liquid phase are avoided.

Issues such like porosity, solute redistribution, solidification cracking and liquation cracking should not arise during stir welding process. Generally, FSW is found to produce a low concentration of defects and is very tolerant to variations in parameters and materials.

Nevertheless, FSW is associated with a number of unique defects if it isn't done properly. Insufficient welding temperatures, due to low rotational speeds or high transverse speeds, for example, mean that the weld material is unable to accommodate the extensive deformation during welding process. This may results in long tunnel-like defects running along the weld, which may occur on the surface or subsurface. Low temperature of may also restrict the forging action of the tool and so reduce the continuity of the bond between the material from each side of the weld.

Friction stir welding and its types – friction stir spot welding and friction stir processing – are used for the following industrial applications: shipbuilding and offshore, aerospace, automotive, rolling stock for railways, general fabrication, robotics, and computers.

Friction stir welding is studied extensively for the past two decades. Mathematical modelling has been of particular interest, as the heat distribution cannot be theoretically determined very easily. The model requires parameters that cannot be easily experimentally determined, so a best fit for these parameters was acquired via regression analysis by comparing the model to experimental data acquired outside of the weld zone.

II. MATHEMATICAL MODEL FOR HEAT TRANSFER

The heat generation during welding process is caused by the mechanical work due to the tool. It is defined by the contact conditions at the interface, and is named as sliding, sticking or partial sliding/sticking conditions. The contact condition between the shoulder and the work piece can be described by sliding friction, using a friction coefficient 'μ' and interfacial pressure 'p' or sticking friction based on the interfacial shear strength at an appropriate temperature and strain rate. Here we are assuming that the total heat generated by the tool is due to both sliding and sticking friction models.

The heat generated at the interface of the work piece and the tool due to friction is $Q_{f\ and}$ that due to plastic deformation is Q_p. Thus, the frictional heat on an elemental area dA at the tool-work piece interface is expressed as

$$dQ_f = (1-\delta)\ \omega t\tau_{contact} dA$$

where, δ is a contact state variable.

Contact state variable is the ratio of velocity of the contact work piece surface with the velocity of the tool surface. The contact state variable is assumed to change linearly with the distance from the centre of the pin. It is expressed as

$$\delta = \frac{v_{workpiece}}{v_{tool}}$$

where, $v_{work\ piece}$ is the peripheral velocity of the work piece.

v_{tool} is the peripheral velocity of FSW tool. ω is angular velocity of tool.

r is radial distance of the elemental area dA from axis.

Physically, δ accounts the amount of frictional work dissipated into the work piece.

The heat generation due to plastic shear deformation Q_p leading to the work piece material sticking to the tool is given by

$$dQ_p = \delta\omega t\tau_{contact} dA$$

Total elemental heat due to friction and plastic deformation in friction stir welding is given by

$$dQ_{FSW} = dQ_p + dQ_f$$

$$= (1-\delta)\omega t\tau_{contact} dA + \delta\omega t\tau_{contact} dA$$

In the case of sliding friction, the contact shear stress, $\tau_{contact} = \mu p$.

The contact shear stress for pure sticking condition is given by

$$\tau_{contact} = \tau_v \ -\frac{a_v}{3^{0.5}}$$

The heat energy generated at the contact interface between a rotating friction stir welding tool and a stationary work piece are subdivided as Q1, Q2 and Q3 on the tool shoulder's surface, tool pin's side surface and tool pin's tip surface, respectively.

The analytical estimation of heat generation from the flat shoulder is expressed as:

$$Q_1 = \iint_{R_{probe}}^{R_{shoulder}} \omega\tau_{contact}\ r^2\, dr d\theta \quad (\text{from } 0 - 2\pi)$$

$$= 0.667\ \pi\ \omega\ \tau_{contact}\ (R_{shoulder}^3 - R_{probe}^3)$$

Heat generation from the probes are expressed as:

$$Q_2 = \iint_0^{R_{probe}} \omega\tau_{contact} \; R^2_{probe} \; drd\theta$$

(from 0-2π)

$$= 2\pi\omega \; \tau_{contact} \, R_{probe}^2 \, H_{probe}$$

$$Q_3 = \iint_0^{R_{probe}} \omega \, \tau_{contact} \; r^2 drd\theta$$

$$= 0.667 \; \pi\omega \; \tau_{contact} \; R_{probe}^3$$

Therefore, the heat generation due to sticking condition with flat shoulder is expressed as

$$Q_{FSW,\,Sticking} = 0.667 \; \pi\omega \frac{av}{\sqrt{3}} \{(R_{shoulder}^3 - R_{probe}^3) + R_{probe}^3 + 3R_{probe}^2 \, H_{probe}\}$$

For the sliding condition, the heat generation is given by

$$Q_{FSW,\,Sliding} = 0.667 \; \pi\omega\mu p\{(R_{shoulder}^3 - R_{probe}^3) + R_{probe}^3 + 3R_{probe}^2 \, H_{probe}\}$$

Thus, the total heat generation due to sliding and sticking is expressed as :

$$Q_{FSW} = \delta \, Q_{FSW,\,Sticking} + (1-\delta) \, Q_{FSW,\,Sliding}$$

Now, for a flat shoulder and straight cylindrical tool, the total heat generation is a linear combination of sliding and sticking condition and is expressed as :

$$Q_{FSW} = 0.667 \; \pi\omega[\mu \, \tau_v + (1-\delta) \, \mu p]\{ (R_{shoulder}^3 - R_{probe}^3) + R_{probe}^3 + 3R_{probe}^2 \, H_{probe}\}$$

There is no straightforward mechanism to estimate the extent of δ. In present case, the contact state variable is calculated by imperial relationship. The extent of slip is estimated by fitting the measured values at various relative velocities and is expressed as:

$$\delta = 0.2 + 0.6[1- \exp(-\delta_0 \frac{\omega r}{\omega_0 R_{shoulder}})]$$

where, δ_0 is an adjustable parameter,

r is the distance of the point from tool axis,

ω is the angular velocity of the tool,

ω_0 is the normalizing rotational velocity which can be taken as the mid-point of the range of rotational speeds.

In present case, δ_0 is considered as 1.014 and other parameters are varied with welding conditions.

The plunging force applied to the plate surface by the tool creates a uniform pressure over the shoulder surface. It is assumed that the distribution of heat flux over the tool shoulder surface varies linearly and in the tool pin surface it varies uniformly. Hence the surface heat fluxes are expressed as :

$$q_{shoulder} = \frac{3Q_1 r}{2\pi R^3_{shoulder}} \quad \text{(at the bottom of the shoulder)}$$

$$q_{pside} = \frac{Q_2}{2\pi R_{probe} H_{probe}} \quad \text{(at the side of the probe)}$$

$$q_{pbottom} = \frac{Q_3}{\pi R^2_{probe}} \quad \text{(at the bottom of the probe)}$$

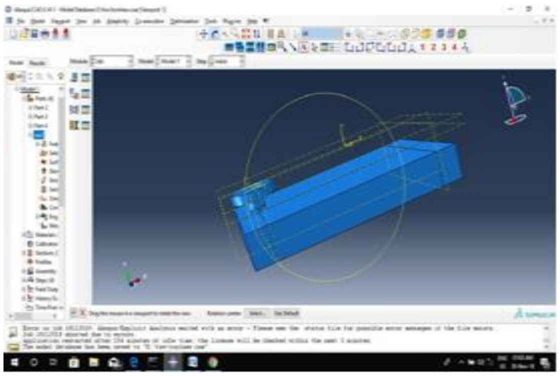
where, $\tau_{contact}$ and δ in the expression of Q1, Q2 and Q3 are applied according to sliding or sticking friction conditions. It is noteworthy that the weight fraction of generated heat from three different surfaces Q1, Q2 and Q3 is estimated based on the geometric parameters of the tool, and sliding and sticking contact condition for all three surfaces.

III. COMPUTATIONAL METHODOLOGY OF MATHEMATICAL MODEL

The thermal simulation of the Friction Stir Welding process is performed using a commercial software ABAQUS. Various journals published and works done on this particular topic has been done using ABAQUS. This software is mainly concerned with simulations of various working models involving loads, forces, thermal effects and deformation with the movement and interaction of parts. ABAQUS does finite element analysis on these parts responsible in the simulation, for their heat transfer, its distribution and energy fluctuations. The fact that we are analyzing welding process led us to opt ABAQUS, that is meant for welding and heat transfer simulations.

The friction stir welding model for which we are conducting the analysis is having the following dimensions:

1. Shoulder diameter :50 mm
2. Probe diameter :12 mm
3. Probe height :9 mm
4. Dimension of plate :200 mm x 100 mm x 13 mm



Fig[1] : The model of friction stir welding apparatus in ABAQUS

The tool material that is used for the experimental analysis is SS304. But for the sake of heat transfer analysis, we use an aluminium body itself as it gives the maximum heat transfer. The plate to be welded is an aluminium 6061 alloy rectangular plate. The shoulder is flat and perpendicular to the work piece. The natural convective heat transfer is considered for the top and side surfaces of the work piece. The procedure of physical modelling is adopted according to the actual experiment where the numerical solution returns the temperature profile in temporal and special domains. FSW process is actually divided into five time instants: plunge time, initial dwell time, welding time, final dwell, and plunge out time. But the major percentage of heat is generated in the welding phase. For the sake of simulation and as the project is limited to the thermal analysis of the welding period.

The methodology of the thermal analysis is to use the formulation obtained in the mathematical modelling to be used in the calculation of heat energy generated during the entire friction stir welding process and obtain the heat transfer in the plate by considering the temperature distribution obtained from the simulation in ABAQUS. For this we consider a circular plate of aluminium that has the dimensions equivalent to the entire tool characteristics as to create the equivalent heat transfer, moving over the aluminium work piece that is of the same dimensions as is required in the original model.

Once these two parts are created, we then define the materials for the plate as well as the tool.

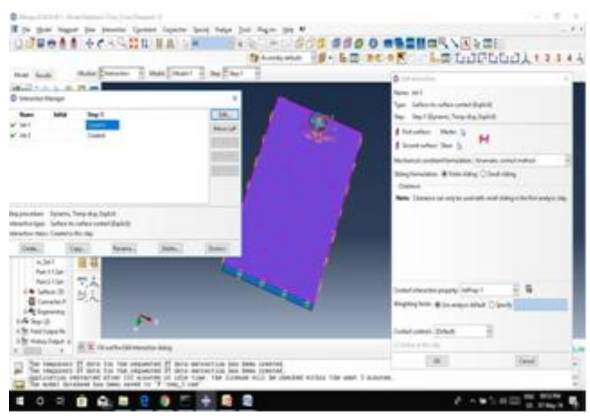
Here, we chose Aluminium 6061 alloy for both the tool and the work piece. It has following properties:

Mass density :2.7E-009 Ton/mm3
Young's Modulus : 70 GPa
Poisson's Ratio : 0.3
Conductivity :0.15 W/mm ℃
Specific Heat : 670000 J/ton/ ℃.

Then we assign the step for the entire welding process. We call that Step-1 which is defined as dynamic, temperature displacement, explicit. We assigned it a time period of 0.1 seconds. This step encapsulates the entire welding procedure.

We proceed with defining the interactions. The interactions involved here are due to contact. We define the mechanical and thermal behaviour.

Mechanical behaviour defines the way it would operate in the presence of contact wi h other surfaces. Friction co-efficient has to be specified in this case. The thermal behaviour defines various heat generations. We then define a set of surfaces, master surface, from which a percentage of heat is being transferred to the slave surface. The points for reference are created and constraints are assigned to them. Another interaction that has to be specified is the surface film condition. Here the condition for surface convection is specified on al sides as well as
the top surface.



Fig[2] : Specifying the interactions in ABAQUS.

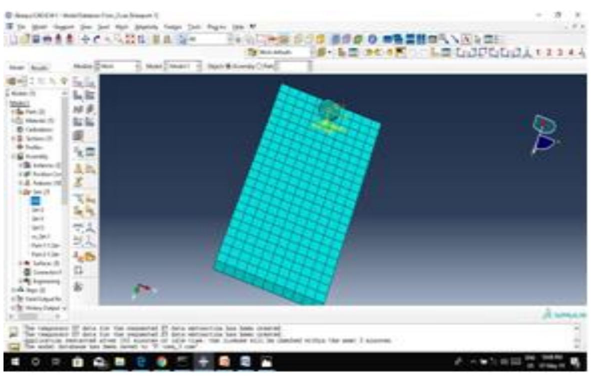
Then we have to specify the loads. In this simulation, the load thermal load is acting on the top of the circular surface. The magnitude of thermal load that has to be applied on the surface is calculated by the heat energy equation obtained in the mathematical modelling. Load has to be calculated in the basis of the equation that has been already covered in Chapter- 4.

$$Q_{FSW} = 0.667\ \pi\omega[\mu\ \tau_y + (1-\delta)\ \mu p]\{\ (R_{shoulder}^3 - R_{probe}^3) + R_{probe}^3 + 3R_{probe}^2 H_{probe}\}$$

The variables that has to be included are the angular speed ω and the plunging force that allows to find the contact pressure between two surfaces.

Then we define the boundary conditions required for the simulation. The boundary conditions are to be defined because they determine the scope and physics of the simulation. Firstly, all the sides and the bottom surface is encastrated, i.e. all the movements are restricted to zero. Then we apply displacement for the circular block on the top of the work piece at 2mm/s.

To carry out meshing, we proceed by defining the mesh, array grid size, type of mesh and the element of mesh. The mesh is defined as HEX and here we chose the coarse mesh and the element of the mesh is Explicit-Couple Temperature Displacement (C3D8t). Various array grid sizes are used according to convenience and need for the simulation. Then we allot initial temperature to all the nodes as 30 ℃ If not defined, it would be taken as 0 ℃.



Fig[3]: After meshing is done.

At the end we define the job and proceed with the data check before submitting and run. The final submission and run gives us the output and end result.

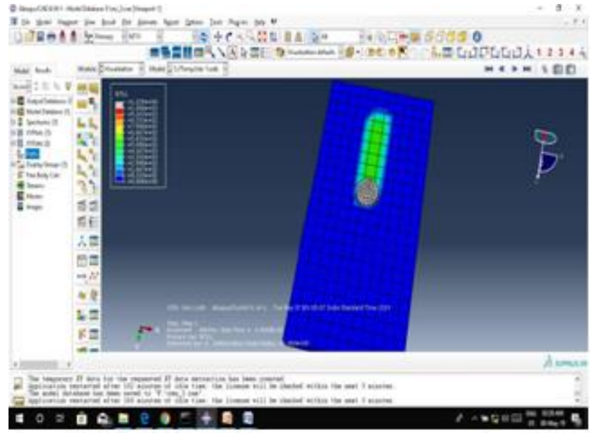


Fig [4]: The model during the results of the simulation

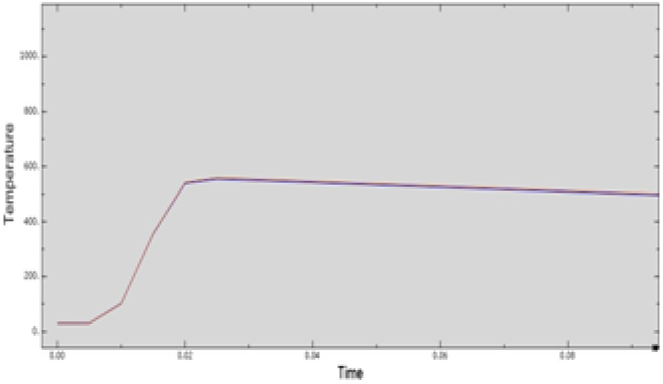
IV. RESULTS & OBSERVATIONS

The results obtained are the temperature distribution at various selected points on the work piece due to the heat transfer between the surfaces. The two points selected are 4.5mm and 10mm from the weld centre line that are offset at 20mm from the starting point of the circular body on the work piece.

Table[1] : Temperature distribution at 4.5 mm from weld line. Where, T_{math} is the temperature at 4.5mm on one side of weld line

Exp. No.	Speed (in rpm)	For the point at a distance of 4.5mm from the weld line	
		T_{math}	T_{math}'
1	914	557.5 □	554.0 □
2	637	545.5 □	537.0 □
3	344	542.0 □	536.0 □

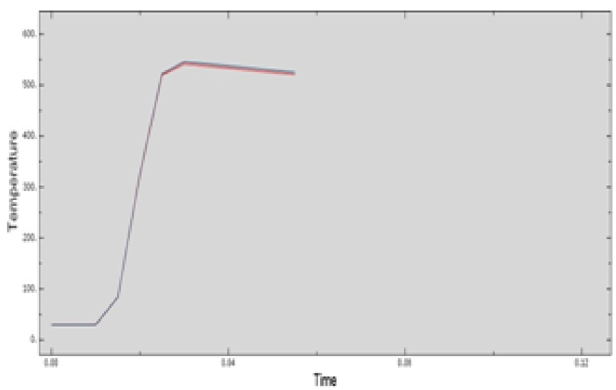
T_{math}' is the temperature at 4.5mm on the other side of weld line.



Graph[1] : Temperature distribution for 914 rpm at 4.5 mm from weld line.

The maximum temperature attained is found to be 570.0 °C.

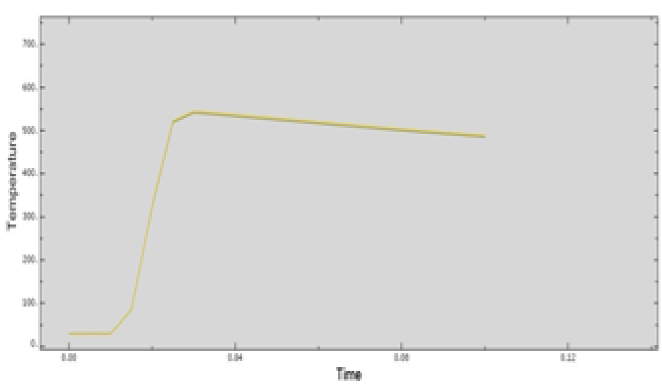
The temperature gradually decreases due to convection as depicted in the graph.



Graph[2] : Temperature distribution for 637 rpm at 4.5 mm from weld line.

The maximum temperature attained is found to be 545.5 °C.

The temperature gradually decreases due to convection as depicted in the graph.



Graph[3] : Temperature distribution for 344 rpm at 4.5 mm from weld line.

The maximum temperature attained is found to be 542.0 °C.

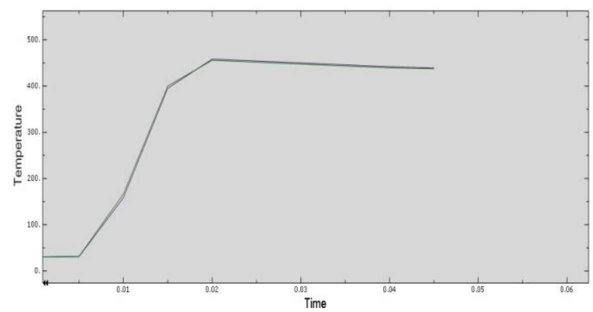
The temperature gradually decreases due to convection as depicted in the graph.

Table [2] : Temperature distribution at 4.5 mm from weld line.

Exp. No.	Speed (in rpm)	For the point at a distance of 10 mm from the weld line	
		T_{math}	T_{math}'
1	914	465.0 □	463.0 □
2	637	438.0 □	418.0 □
3	344	429.0 □	410.0 □

where, T_{math} is the temperature at 4.5mm on one side of weld line.

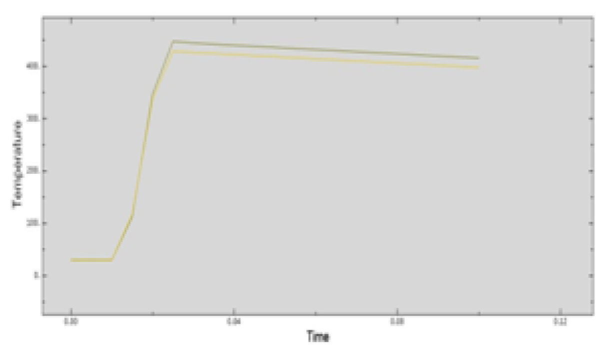
T_{math}' is the temperature at 4.5mm on the other side of weld line.



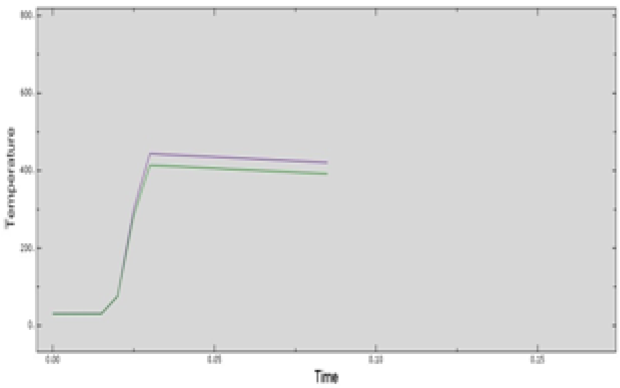
Graph[4] : Temperature distribution for 914 rpm at 10 mm from weld line.

The maximum temperature attained is found to be 465.0 °C.

The temperature gradually decreases due to convection as depicted in the graph.



Graph[5] : Temperature distribution for 637 rpm at 10 mm from weld line.



Graph[6] : Temperature distribution for 344 rpm at 10 mm from weld line.

The maximum temperature attained is found to be 429.0 ℃.

The temperature gradually decreases due to convection as depicted in the graph.

V. CONCLUSION

The literature review of the researches done in connection with the topic was flooded with immense research and advancements that has already been in this field. It helped in the deep understanding of the concepts as well as the theoretical and practical means of analysing friction stir welding. Mathematical modelling of the process was done based on the theoretical aspects and basic thermodynamics. The main aim of mathematical modelling was to formulate the equations to find out the heat generated in the welding process.

The simulation for the mathematical model formulated was set up, considering the boundary conditions, interactions and meshing. The heat energy equation obtained from the mathematical model had to be solved to be applied in the simulation. Using this heat energy, a body having this amount of heat energy was made to move over the work piece at different rpm s. This simulation gave the temperature distribution in the work piece.

This temperature distribution was found to be complying to the experimental values that were taken from reference (1). It was also found out that the temperature distribution is not necessarily symmetric with respect to the weld line centre. The errors were found to be within the permissible range. Thus, the mathematical model so created was found to be apt to the conditions and parameters of the friction stir welding apparatus and thus the modelling is done its validation.

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