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RESEARCH ARTICLE

ANALYSIS OF FRICTION STIR WELDING PROCESS FOR 304L STAINLESS STEEL

[1]Swapnil J. More and [2*]Niyati Raut

[1]VIVA institute of Technology Shirgaon, Veer Sawarkar road, Virar (East), Tal- Vasai, Dist-Thane, Maharashtra, India
[2]Faculty of Engineering, University of Mumbai, India

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ABSTRACT

This paper focusses on Friction stir welding (FSW) invented by Wayne Thomas in The Welding Institute (TWI) at London in 1991. Friction stir welding (FSW) is a solid state joining process which means joining of metal plates without reaching the melting point of the material to be welded. FSW uses a non-consumable rotating tool which is plunged into workpiece material due to which heat is generated between tool shoulder and workpiece surface which results in plastic deformation of material to be welded. This technique of joining metal is energy efficient, environmental friendly and can be used to join high strength aluminium alloys and other alloys that are hard to weld by conventional fusion welding. The paper focuses on performing simulation using Ansys for joining 304L stainless steel plates, to obtain better quality of welds by varying the input process variables.

INTRODUCTION

The heat transfer process is one of the most important aspects in the FSW study. A good understanding of the heat transfer process in the work piece can be helpful in predicting the thermal cycles in the welding work piece, and the hardness in the weld zone, subsequently, can be helpful in evaluating the weld quality. In this process, the heat is originally derived from the friction between the welding tool (including the shoulder and the probe) and the welded material, which causes the welded material to soften at a temperature less than its melting point. The softened material underneath the shoulder is further subjected to extrusion by the tool rotational and transverse movements. It is expected that this process will inherently produce a weld with less residual stress and distortion as compared to the fusion welding methods, since no melting of the material occurs during the welding. Despite significant advances in the application of FSW as a relatively new welding technique for welding, the fundamental knowledge of thermal impact and thermo mechanical processes are still not completely understood. To study the variations of transient temperature and frictional heat developed in friction stir welding of 304L stainless steel plates, detailed three-dimensional nonlinear thermal and thermo-mechanical simulations are performed for the FSW process using Ansys APDL by varying input process variables tool rotational speed and tool linear velocity. Simulation of FSW process is carried out using Ansys APDL. A nonlinear direct coupled-field analysis is performed, as thermal and mechanical behaviours are mutually dependent and coupled together during the FSW process. Because the temperature field affects stress distribution a fully thermo-mechanically coupled model is created. The model consists of a coupled-field solid element with structural and thermal degrees of freedom. The model has two rectangular steel plates and a cylindrical tool. All necessary mechanical and thermal boundary conditions are applied on the model. The simulation occurs over three load steps, representing the plunge, dwell, and traverse phases of the process. The temperature rises at the contact interface due to frictional contact between the tool and workpiece. FSW generally occurs when the temperature at the weld line region reaches 70 to 90 percent of the melting temperature of the work piece material. The temperature obtained around the weld line region in this analysis falls within the range reported by Zhu and Chao, while the maximum resulting temperature is well below the melting temperature of the workpiece. A bonding temperature is specified at the contact interface of the plates to model the welding behind the tool. When the temperature at the contact surface exceeds this bonding temperature, the contact is changed to bonded. The tool pin is ignored. The heat generated at the pin represents approximately two percent of the total heat and is therefore negligible. The FSW process generally requires a tool made of

Corresponding author: Niyati Raut,
VIVA institute of Technology Shirgaon, Veer Sawarkar road, Virar (East), Tal- Vasai, Dist-Thane, Maharashtra, India.

a harder material than the workpiece material being welded. In the past, FSW was used for soft workpiece materials such as aluminium, with the development of tools made from super-abrasive materials such as polycrystalline cubic boron nitride (PCBN), FSW has become possible with high-temperature materials such as stainless steel. A cylindrical PCBN tool is modeled in this case. The workpiece sides parallel to the weld line are constrained in all the directions to simulate the clamping ends. The bottom side of the workpiece is constrained in the perpendicular (z) direction to simulate support at the bottom. Heat losses are considered on all the surfaces of the model. All boundary conditions are symmetric across the weld centerline. The simulation is performed in three load steps, each representing a respective phase (plunge, dwell, and traverse) of the FSW process.

Problem Definition

Friction stir welding is latest technology in industry and it has many advantages on traditional welding technologies. Normally metals and alloys are joined by fusion welding process. All fusion welding processes (particularly for materials having low weldability such as copper) are characterized by welding defects and Some metals like Al, Cu and Mg alloy series are not at all fusion weldable. Also Welding of different materials and much different in thickness are impossible/very difficult with fusion welding process. Main drawback of FSW process is that selection of correct input parameters to insure good weld quality. Generally this selection is based on trial and error method. Now the rotational speed, linear travel speed and downward force of the tool are the process parameters which need to be controlled to get good quality of weld. The downward force of the tool is kept constant while the rotational and linear speed is varied for heat generation beneath the tool shoulder. Downward force of the tools helps to achieve proper frictional contact. The selection of other two process parameters are generally selected on trial and error method so the need is to perform simulation to predict the process parameters that are rotational speed and linear speed to achieve good quality of weld and to find out frictional heat developed during welding. Thermomechanical model developed by Zhu and Chao for friction stir welding of 304L stainless steel is replicated using ANSYS. The developed model is then used to conduct parametric studies to understand the effect of various input parameters like rate of tool velocity and tool rotational speed on temperature distribution developed in the work piece.

The objective is to study the effect of tool rotation speed and tool linear velocity on the maximum temperature and frictional heat developed during the welding process. The heat developed during the welding process depends on the friction between tool and the workpiece. 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 considered 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 project focuses on investigation of input parameters that control the welding temperature in 304L stainless steel friction stir welds and on model-based optimization of the process.

Proposed layout

Fig. 1. Layout for model creation and performing analysis using Ansys

Thermo mechanical model of FSW

The Finite Element Method (FEM) offers a way to solve complex continuum problems by subdividing it into a series of simple interrelated problems. FEM is most commonly used in numerical analysis for obtaining approximate solutions to wide variety of engineering problems. In the present study, a commercial general purpose finite element program ANSYS® 14.5 was used for numerical simulation of friction stir welding process.

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,

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

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.

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 centerline.
- 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 as shown in Fig 2.

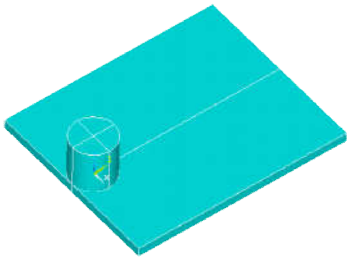


Fig. 2. Geometry of workpiece

Element used

In the present thermal analysis, the workpiece is meshed using a brick element called SOLID 226. This element has a three-dimension thermal conduction capability and can be used for a three- dimensional, steady-state or transient thermal analysis. The element is defined by eight nodes with temperature as single degree of freedom at each node and by the orthotropic material properties. Heat fluxes or convections (but not both) can be input as surface loads at the element.

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.

Boundary conditions

Boundary condition for FSW thermal model were specified as surface loads through ANSYS codes. Assumptions were made for various boundary conditions based on data collected from various published research papers (Zhu and Chao, 2004). Convective and radiative heat losses to the ambient occurs across all free surfaces of the workpiece and conduction losses occur from the workpiece bottom surface to the backing plate. To consider convection and radiation on all workpiece surfaces except for the bottom, the heat loss q_s is calculated by following equation 2,

$$q_s = \beta(T - T_0) + \varepsilon\beta(T^4 - T_0^4) \qquad \text{.....................} (2)$$

Where, T is absolute temperature of the workpiece, T_0 is the ambient temperature, β is the convection coefficient, ε is the emissivity of the plate surfaces, and ς= 5.67 x 10-12 Wcm^2°C is the Stefan-Boltzmann constant. In the current model, a typical value of β was taken to be 10 Wm^2°C using an ambient temperature of 300 K and ε was taken to be 0.17 for 304L steel. In order to account for the conductive heat loss through the bottom surface of weld plates, a high overall heat transfer coefficient has been assumed. This assumption is based on the previous studies (Zhu and Chao, 2004; Yuh *et al.,* 2003). The heat loss was modeled approximately by using heat flux loss by convection q_b given by following equation 3,

$$q_b = \beta_b(T - T_0) \qquad \text{......................................} (3)$$

Where βb is a fictitious convection coefficient

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°C. Fig. 3 Schematic representation of boundary condition for thermal analysis.

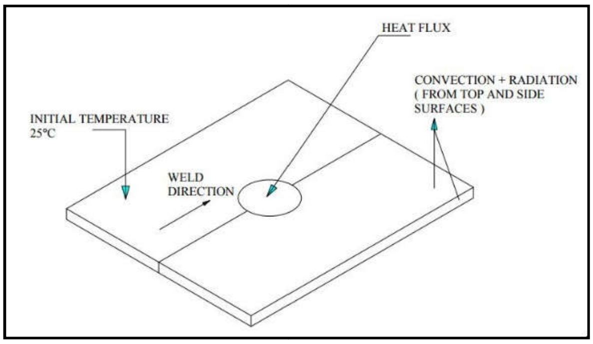


Fig. 3. Schematic representation of boundary condition for thermal analysis

Heat is produced in the friction stir welding process due to the friction between the tool shoulder and workpiece interface and due to the plastic deformation of the model weld metal near the pin. The heat generated by the plastic deformation of weld metal near the pin is of negligible magnitude and is difficult to quantify (Yuh *et al.,* 2003). Hence, it was neglected in this study. Therefore in this, the heat generated by friction between the workpiece and tool shoulder is the only source of heat generation. The total heat input Q in watts for this model is calculated through (Yuh *et al.,* 2003) equation and is applied as a moving heat flux. The total heat input Q is given by following equation 4,

$$Q = \frac{\pi\omega\mu F(r_o^2 + r_o r_i + r_i^2)}{45(r_o + r_i)} \qquad \text{...........................} (4)$$

Where, ω is the tool rotational speed, μ is the frictional coefficient, F is the downward force, r_o and r_i are the radii of the shoulder and the nib of the pin tool. The rate of heat input to the workpiece q(r) is assumed to be axis-symmetric and linearly distributed in the radial direction (Yuh *et al.,* 2003) and is calculated by equation 5,

$$q(r) = \frac{3Qr}{2\pi\left(r_o^3 - r_i^3\right)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In the present simulation, the heat flux q(r) obtained from the above equation is applied as surface load using tabular boundary condition. The movement of FSW tool is implemented by creating a local cylindrical coordinate system and calculating heat load at each node at each instantaneous time step. The dimensions for tool and values for other parameters used in this study were obtained from (Zhu and Chao, 2004) for correlation to the published research data. The tool shoulder diameter used in this study was 19.05 mm, while the pin diameter was assumed as zero. The assumption was made based on findings from Russell and Sheercliff that the heat generated at the pin of the tool is in the order of 2% of total heat and hence negligible. Fitted values of Q and β_b were used in this study.

Mechanical model

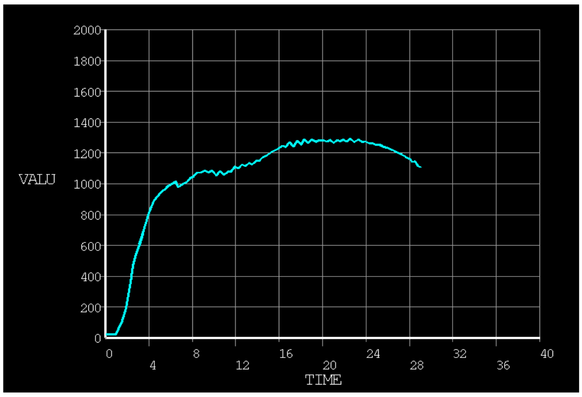
The following assumptions have been made in developing the structural model:

- Deformation occurs symmetrically along the weld line, so only half of the workpiece is modeled.
- The plate material is homogeneous.
- The effect of creep is neglected because there is no cyclic thermal load involved.

RESULTS AND DISCUSSION

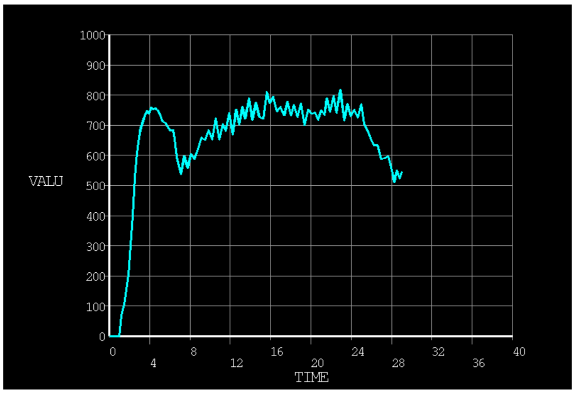
The values of input parameters are increased by 10% and the results were plotted.

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

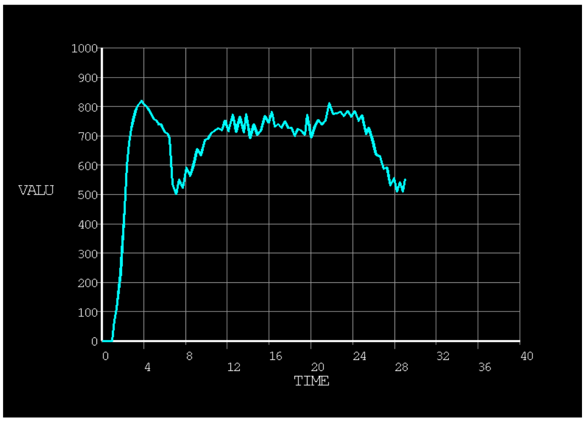


Graph 4.1 Temperatures vs. Time (60 rpm)
It is observed that temperature slowly increases with time. It reaches maximum temperature at 18 sec after the process started and corresponding temperature is 1300°c.

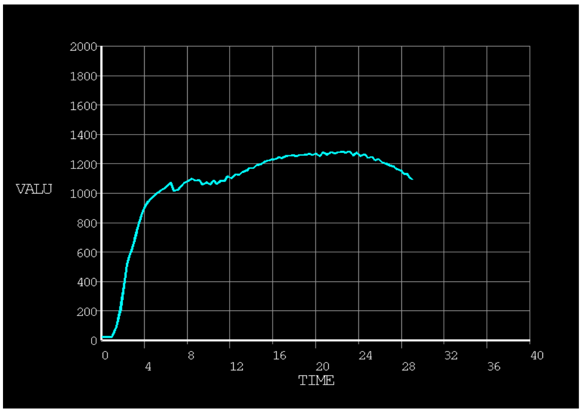
Graph 4.2 Frictional heat vs. Time (60 rpm)
Friction between tool and the workpiece generate heat. The maximum temperature generated due to friction is about 820°J. (Graph 4.2)



Analysis with 66 rpm and 2.71 mm/s tool velocity



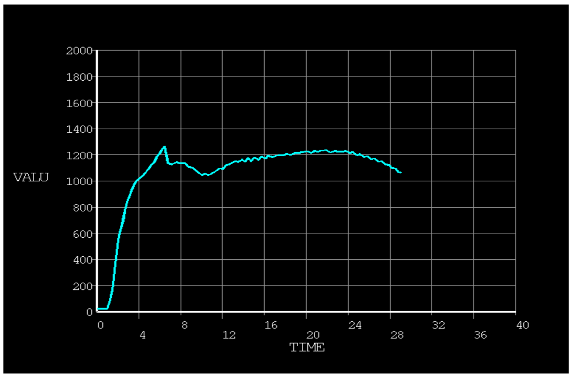
Graph 4.3 Temperatures vs. Time (66 rpm)
The Temperature variations are shown in the graph. For first few seconds the temperature increases linearly, after 4 sec there is sudden decrement in the welding temperature. After 7 seconds temperature rises.



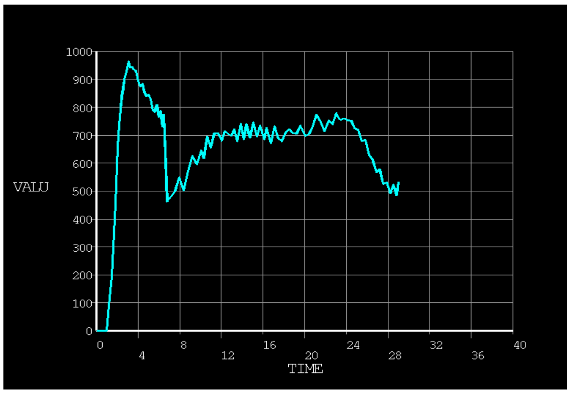
Graph 4.4 Frictional heat vs. Time (66 rpm)
Fiction heat is increases with time but is will slightly decreases at the end of the process.

Analysis with 78 rpm and 2.71 mm/s tool velocity

Graph 4.5 Temperatures vs. Time (78 rpm)
For first few seconds temperature increases linearly then there is sudden drop in the temperature. The temperature achieve during initial stage is the maximum temperature.



Graph 4.6 Frictional heat vs. Time (78 rpm)
Maximum friction heat is between 900 to 1000J.



Conclusions

Non-linear Thermo-coupled analysis was use to find temperature and friction heat in welding process. It is observed that tool rotation speed and tool velocity plays an important role in friction stir welding process.

- As the rotation speed of the tool increases, maximum temperature decrease because of increase in convection due to tool rotation.
- Increased rotation speed also increases the friction heat developed between tool and the workpiece.
- For better weld we suggest higher tool rotation speed and lower tool velocity.

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