Finite-Element modeling of Thermo-Mechanical phenomena in friction stir welding of AISI 4340 steel

Olanipekun Ayorinde Tayo,
Department of Mechanical and Industrial Engineering
University of Johannesburg, South Africa,
atolanipekunayo@uj.ac.za

Timothy O. Laseinde,
Department of Mechanical and Industrial Engineering
University of Johannesburg, South Africa
otlaseinde@uj.ac.za

Madindwa Mashinini
Department of Mechanical and Industrial Engineering
University of Johannesburg, South Africa
mmashinini@uj.ac.za

Abstract

Most metallic alloys that are not easily joined by conventional fusion welding are usually joined by friction stir. on this basis, friction stir welding has seen a wide application in different industry. Friction stir welding is complex phenomena having connected physical phenomena. However, it is usually difficult to theoretically develop a system of governing equation to analyze friction stir welded joint, due to the three-dimensional nature and complex geometry. Also, the experimental techniques are often time consuming and costly. Meanwhile, numerical analysis has been introduced to overcome these problems. This study presents a straightforward perspective to friction stir welding (FSW) of AISI 4340 steel alloy numerical modeling and simulation. A three-dimensional heat transfer model for FSW was presented, the coordinate system was considered as a moving one, while the tool axis is fixed. Stationary convection-conduction was adopted to solve heat transfer problem. The Heat generated between the interface between the tool pin the work piece was simulated using model created in COMSOL Multiphysics software V 4.0.

Keywords
Friction stir welding, steel, Heat transfer, modeling and simulation

1. Introduction

Friction stir welding (FSW) is a solid state joining process, invented by the welding institute of Cambridge, as a solid state joining techniques (Sorensen 2001, Thomas et al. 1991) .
FSW process consist of a rotating tool pin that move with the help of a shoulder, aiding the translatory motion, to thrust into a joint between two work pieces, producing heat by friction in return, that plasticized the base material (Sorensen and Nelson 2007).
However, FSW process has been developed overtime to process materials with high stresses and high melting points materials, such as Nickel- base alloys like steels, and stainless steels (Sorensen and Nelson 2007, Thomas et al. 1999). Also, It favored joining technique for difficult metals that are laborious to weld like magnesium alloys (Cao and Jahazi 2011, Chowdhury et al. 2010)
The Heat flux in the FSW process is known to be basically generated by deformation and the friction process, it also known fact that the tool and the work piece contribute to the heat generated. Also, having a better grasp of the FSW heat transfer process is mandatory, because inadequate heat from the friction, can result to the tool pin breakage, since the material is not soft enough. The amount heat taken in by the weld goes a long way to determine the quality of the weld, micro-structure of the weld, thermal distortion, the shape of the weld, and residual stress (Chao et al. 2003). Furthermore, having a vivid understanding of heat transfer in FSW process is salient, especially in improving the process of welding, predicting thermal cycle in the weld piece and also understanding heat transfer mechanism in the work piece (Song and Kovacevic 2003).
AISI 4340 steel alloy has a moderate strength and medium hardness (Gurumurthy et al. 2018). They are also classified under the categories of high strength low alloy steel (HSLA) with high and good fatigue strength at elevated temperature, all this top-notch property enables AISI 4340 to find applications in navy critical structure, automobile parts and pressure vessel (Jasthi et al. 2015).
In this current research paper, we present a study on the heat transfer of the FSW process for both AISI 4340-steel workpiece and the tool.

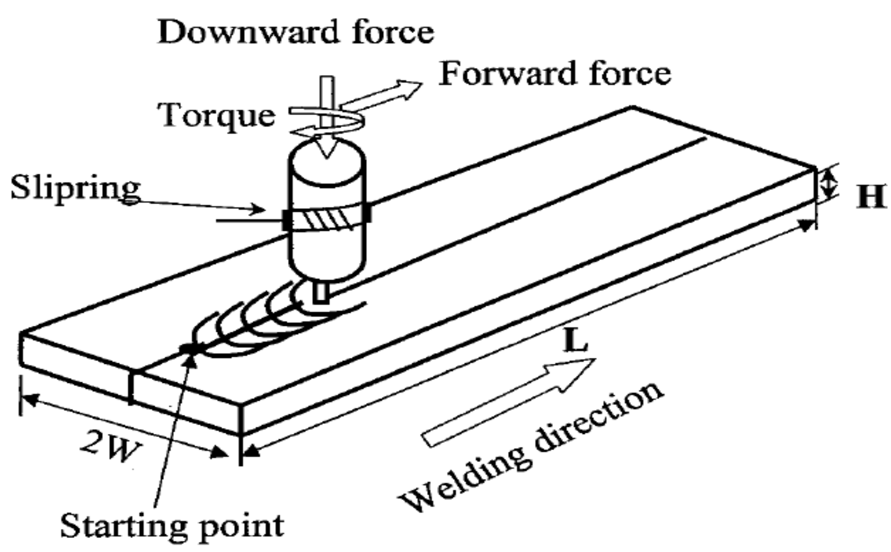

Figure 1. Diagram showing FSW process (Chao et al. 2003)

2. MATHEMATICAL MODEL

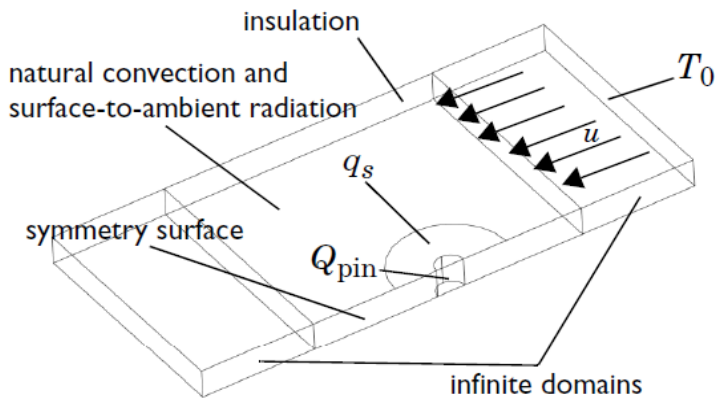

Figure 2. Model geometry for friction stir welding.

It was assumed the model to be symmetrical around the weld. Modeling only one steel plate is therefore adequate, also the coordinate transformation assumes that the steel plates are infinitely long, neglecting the effects around the plate's edges, also the material flows from the frontage end to the back of the rotating tool and phase changes are not considered in the model. The plates dimensions are 80mm by 60mm and 5mm, guarded by the infinite domains in the x direction as shown in figure 2.
Heat transfer in the plates is describes by the following equations. The equation includes a conductive and convective terms, while fixing the coordinate system [9].

$$\nabla \cdot (-k\nabla T) = Q - \rho C_P \boldsymbol{u} \cdot \nabla T \qquad 1$$

Thermal conductivity is represented by k, ρ is the density, C_P represent specific heat capacity and $\boldsymbol{u}$ is the velocity.

$$q_{in}(T) = \frac{\mu}{\sqrt{3(1+\mu^2)}} r_p \omega \bar{Y}(T) \quad (W/m^2) \qquad 2$$

μ is the friction coefficient, while r_p denotes the pin radius, angular velocity is represented by ω measured in (rad/s), and $\bar{Y}(T)$ is the average shear stress of the material as the function of the temperature.

The equation below defines heat flux (W/m^2) per unit area as a function of distance r from the axis center of the tool.

$$q_{shoulder}(r,T) = \begin{cases} \left(\frac{\mu F_n}{A_s}\right)\omega r; T < T_{melt} \\ 0 \qquad ; T \geq T_{melt} \end{cases} \qquad 3$$

The shoulder's surface area is represented by A_s, F_n normal force acting, T_{melt} is the steel melting point temperature, ω is the angular velocity of the tool (rad/s) and μ is the frictional coefficient.

When the temperature is above the melting temperature of the steel, the tool and the steel plate exhibit low melting temperature. Both the lower surface and the upper surface of the steel plates will lose heat, owing to natural convection and surface-to-ambient radiation. Heat flux expressions can be represented by the equation below [11].

$$q_{up} = h_{up}(T_0 - T) + \varepsilon\sigma(T_{amb}^4 - T^4) \quad 4$$

$$q_{down} = h_{down}(T_0 - T) + \varepsilon\sigma(T_{amb}^4 - T^4) \quad 5$$

h_{up} and h_{down} are heat transfer coefficients for natural convection, σ is the Stefan-Boltzmann constant, ε is the surface emissivity, T_{amb} is the ambient air temperature, while T_0 is the reference temperature.

Table 1: Physical properties of the AISI 4340 steel

Property	Values
Thermal conductivity	44.5 W/mK
Density	7850$K\ g/m^3$ kg/m3
Heat capacity at constant pressure C_p	475 $J/kg * K$

Table 2: Thermophysical properties and physical parameters

Description	Values
Ambient temperature (T_0)	300K [9]
Work piece melting temperature (T_melt)	1073K (Giorjão et al. 2018)
Heat transfer coefficient upside (h_upside)	500 W/m^2 (Giorjão et al. 2018)
Heat transfer coefficient upside ($h\_downside$)	2000 W/m^2 (Giorjão et al. 2018)
Surface emissivity (ε)	0.3 (Giorjão et al. 2018)
Welding speed (u_weld)	50mm/min(Santos et al. 2016)
Friction coefficient (mu)	0.4(Song and Kovacevic 2003)
Rotation speed(RPM)	600(Santos et al. 2016)
Normal force (F)	40kN(Santos et al. 2016)
Pin radius	7.72mm
Pin shoulder	25mm

Table 3: Material property of the pin h [9]

Property	**Values**
Thermal conductivity	$42W/mK$
Density	$7800Kg/m^3$ kg/m3
Heat capacity at constant pressure C_p	$500J/kg * K$

3. RESULT AND DISCUSSION

3.1. Result

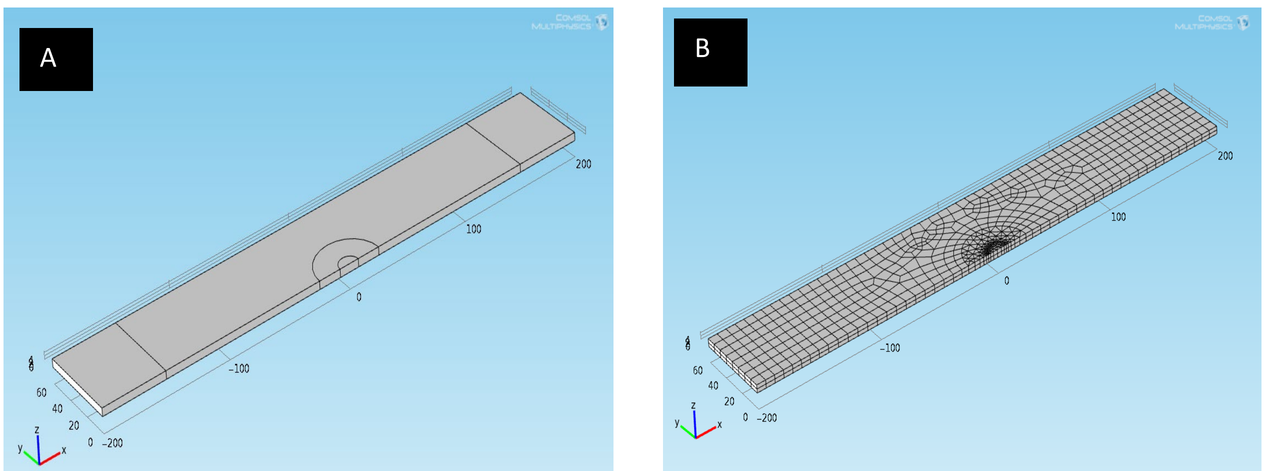

Figure. 3. Model (A) Boundary conditions in the heat transfer model (B) Mesh profile

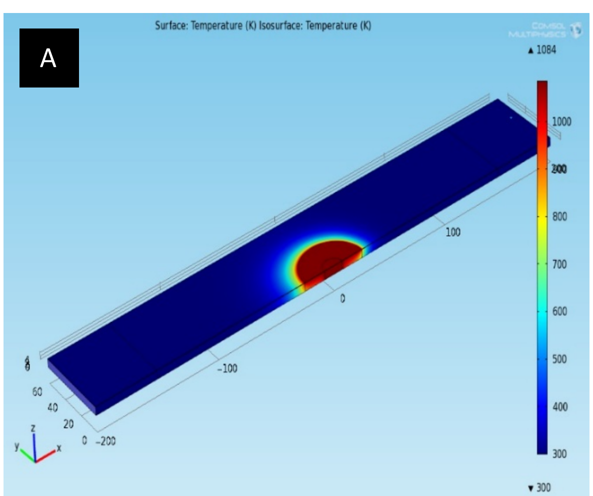

Figure. 4. Temperature field in the steel plate

3.2. Discussion

Figure 3A, shows the original model geometry drawn using the Computer aided design tools (CAD) in comsol Multiphysics. Figure 3B shows the mesh model discretized using free quad and free triangular operation with extremely fine size, to enable easy convergence.
From Fig 4A, the temperature history of the workpiece was shown during the pin penetration, it was noticed that the temperature was of the highest value where the steel is in contact with the rotating tool in agreement with the work of Song and Kovacevic (Song and Kovacevic 2003). The penetration speed was set to be 50mm/min at rotation speed 600 rpm. However, directly in front of the tool new cold materials enters, while hot materials are transported away behind the tool.

Assumptions

1. Heat is generated at the interface between the work piece and tool's shoulder.

2. Symmetry is assumed along the boundary of the weld joint.

3. The steel plates are assumed to be infinitely long.

It should also be noted that the analysis did not factor in the stirring process and material flow in the steel. The material property of the AISI 4340 was gotten from predefined materials properties in Comsol Multiphysics software V 4.0, while heat transfer coefficients and other physical properties are gotten from empirical expression available in the literature.

4. Conclusion

A three-dimensional steel plate model surrounded by two infinite domains in the x-direction has been modeled in this paper. The model results show heat generated between the steel plate and the FSW tool pin.

The following are the conclusions drawn,

A. The model can find application in modeling combine heat transfer process for the work piece and the tool during FSW.

B. Modelling of temperature distribution between the tool and the work piece has been simplified.

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Biographies

Olanipekun Ayorinde, currently having his PhD research at the University of Johannesburg, Mechanical Engineering Department. He has a lot of experience in computational material science analysis, phase field modeling, Finite

Element Analysis, Data science, Quantum Machine Learning. He also has worked for 7 years' in an Engineering research institute, where he learnt most of his computational skills.
Timothy Laseinde has a PhD in Mechanical Engineering. He currently holds a position of Senior lecturer at Mechanical and Industrial Engineering Department, University of Johannesburg, South Africa. His research interests include manufacturing, simulation, optimization, Virtual learning, Fourth Industrial Revolution, and Machine Design, a registered member of "The south African Institution of Mechanical Engineering (SAIMechE)".

Madindwa Mashinini Currently sits as the Head of Department of Mechanical and Industrial Engineering Department, University of Johannesburg. He has a lot of experience in material testing and structural evaluation (macro and micro analysis). Also, his research interests are in material processing and manufacturing techniques. Material processing is on friction stir processing and laser beam welding of light metals which include but not limited to Titanium and Aluminium alloys. He has presented his research work both locally and in an international conference, also published in various ISI journals. A registered member of "The south African Institution of Mechanical Engineering (SAIMechE)".