NUMERICAL MODELING AND SIMULATION OF FRICTION STIR PROCESSING OF AA1100

A report on

PRIR16 INTERNSHIP / INDUSTRIAL TRAINING

by

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December 2021

BONAFIDE CERTIFICATE

This is to certify that **PRIR16 INTERNSHIP / INDUSTRIAL TRAINING**

project titled "NUMERICAL MODELING AND SIMULATION OF FRICTION STIR PROCESSING OF AA1100"

is a bonafide record of the work done by

Jayendran R (114118040)

In partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Production Engineering of the NATIONAL INSTITUTE OF TECHNOLOGY, TIRUCHIRAPPALLI, during the year 2018-2022.

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উন্নত উৎপাদন প্রযুক্তি শ্রেষ্ঠত্ব কেন্দ্র

৫ ম তল, সিআরআর ভবন **ভারতীয় প্রযুক্তি প্রতিষ্ঠান খড়াপুর** খড়াপুর ৭২১৩০২, পশ্চিমবঙ্গ, ভারত

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December 21, 2021

<u>To Whom It May Concern</u>

This is to certify that **Mr. Jayendran Ravindran**, an undergraduate student of Production Engineering Department of National Institute of Technology, Tiruchirappalli, worked under my supervision during his internship from June 2021-till Present in online mode.

Mr. Jayendran has worked under my supervision in "Numerical modeling of corrosion in Friction Stir Processing".

He simulated the temperature generation in the friction stir processed aluminium plate, found out current density, corrosion potential, corrosion rate in the aluminium plates after friction stir processing.

Mr. Jayendran is a hard-working and accomplished student. He is determined to achieve a good learning curve despite the whole experience being in the virtual mode. He has never failed to explore new domains or learn new software if the project demanded it. The rapidly escalating progress has made evident that he worked hard to achieve the solution.

It is hereby declared that the said internship is not a part of the academic curriculum of the institute where Mr. Jayendran studied in. This internship is non-remunerative.

The undersigned may be contacted for further information about the intern.

I wish Mr. Jayendran all the success in his academic career.

Thanking you

Sincerely

Professor Surjya K Pal

Lord Kumar Bhattacharyya Chair Professor in Manufacturing Professor, Department of Mechanical Engineering Chairperson, Centre of Excellence in Advanced Manufacturing Technology Associate Dean, Alumni Affairs and Branding Professor-in-Charge, Metrology and Friction Stir Welding Laboratories

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ABSTRACT

Friction Stir welding is a solid-state welding process, i.e., joins two metallic plates without melting. In FSW, heat is generated below the melting temperature of metal, which leads to plasticization of the metallic surfaces in contact. The heat is generated by stirring effect of tool pin rotation. The plasticization leads to the metal flow around the pin, causing the two metallic surfaces to join.

During FSW, plastic deformation takes place to stirring action and increased temperature and metal flows around the tool pin, causing the microstructure to change appreciably. The change in microstructure causes appreciable change in material properties. The aim of this project was to deduce surface temperature and corrosion rate of FSW-ed plates.

The first module deals with thermal modelling of FSW-ed Al-Al plates. The second module deals with corrosion analysis of FSP-ed AA1100 sheets and FSW-ed Al-Al sheets.

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ABBREVIATIONS

 $FSW-Friction \;Stir\;Welding$

- FSP Friction Stir Processing
- AA1100 Aluminium Alloy Series 1100

NOTATIONS

 T_{melt} = Melting temperature of AA1100

 $T_0 =$ Temperature at t=0

 $T_{amb} = Ambient temperature$

T = Surface temperature

 q_{pin} = Heat generated by pin

 $q_{shoulder}$ = Heat generated by shoulder

 q_u = Heat loss at top surface

 q_d = Heat loss at bottom surface

 h_u = Heat coefficient at top surface

 h_d = Heat coefficient at bottom surface

 $r_{pin} = Radius of pin$

 $r_{\text{shoulder}} = \text{Radius of shoulder}$

Y(T) = Temperature dependent yield stress of AA1100

 μ = Friction coefficient

u_weld = Welding speed (m/s)

N = Rotational speed (RPM)

Fn = Normal force

As = Surface area

 $\varepsilon =$ Surface emissivity

 σ = Thermal conductivity

F = Faraday's constant (96500 C mol⁻¹)

 φ = Electric potential

Icorr = Corrosion current density

Gsize = Grain size

A_cat = Equilibrium current density, cathode

A_an = Equilibrium current density, anode

i0_cat = Equilibrium potential, cathode

i0_an = Equilibrium potential, cathode

CHAPTER 1

INTRODUCTION

Friction Stir welding:

Friction stir processing is a solid-state fusion process, which can modify the microstructure and bring the ideal material properties. In FSP, a non-consumable tool is plunged and rotated along its axis, thus generating frictional heat. As the metal reaches plasticization temperature, which is 70-90% of its melting temperature, the metal plastically deforms and fuses with other metal surfaces. Material properties are affected by FSP due to plastic deformation. Hence, various process parameters such as welding speed, rotation speed, dimensions of tool pin and shoulder and axial force determine the microstructure and corrosion resistance of the welded region.

FSP tool consists of tool pin with circular profile and shoulder on which the pin is mounted. The tool pin is plunged, rotated, and moved along the region. The metal deforms and flows around the pin, which leads to joining of two metal surfaces. One of the common materials used for FSP is Aluminium alloy 11xx series.

AA1100 is commonly used in aerospace and automotive industries for their high strength-to-weight and high corrosion resistance. Friction Stir Processing of AA1100 plates induces changes in material properties such as grain size and corrosion resistance. Our aim is to predict the corrosion resistance of friction stir processed aluminium plates through numerical modelling and simulation.

CHAPTER 2

METHODOLOGY

Thermal modelling:

Two assumptions are taken for the thermal model. The workpiece material is considered homogeneous and isotropic. No melting takes place during the friction stir processing. Thermal model is developed to find the surface temperature, corresponding to various process parameters and validate the model.

This is the diagram of the simulation to be done in COMSOL Multiphysics.



Fig.1 FSW process of Al-Cu metallic plates

This is the modelling of the above diagram. The sheet is assumed to be infinitely long and stirring process is not accounted for. The welding is symmetric in model geometry. So, the dimensions of each sheet are 300×100 mm with the width of 0.5mm, surrounding by infinite domain in both the x-directions.



Fig.2 Thermal modelling of FSW process

Governing Equations:

Heat transfer equation for FSW:

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q$$

Heat generated between tool's pin and workpiece

$$q_{\rm pin}(T) = \frac{\mu}{\sqrt{3(1+\mu^2)}} r_{\rm p} \omega \overline{Y}(T)$$

Heat generated between tool's shoulder and workpiece

$$q_{\rm shoulder}(r,T) = \begin{cases} (\mu F_{\rm n}/A_{\rm s}) \varpi r & \text{ if } T < T_{\rm melt} \\ 0 & \text{ if } T \geq T_{\rm melt} \end{cases}$$

This heat generation will become zero if temperature is greater than melting temperature of the metal.

Boundary Conditions:

The heat flux boundary condition for the workpiece at the tool shoulder/workpiece interface is

$$k \frac{\partial T}{\partial n}\Big|_{\Gamma} = q_P$$

The heat flux boundary condition at the tool pin / workpiece interface is

$$k \frac{\partial T}{\partial n}\Big|_{\Gamma} = q_s$$

The convection boundary condition for all the workpiece surfaces exposed to the air can be expressed as

$$k \frac{\partial T}{\partial n}\Big|_{\Gamma} = h(T - T_0)$$

Heat loss due to natural convection and surface-to-ambient air radiation is accounted by

$$T(x,y,z,0) = T_i$$

$$\begin{aligned} q_{\mathrm{u}} &= h_{\mathrm{u}}(T_0 - T) + \varepsilon \sigma (T_{\mathrm{amb}}^4 - T^4) \\ q_{\mathrm{d}} &= h_{\mathrm{d}}(T_0 - T) + \varepsilon \sigma (T_{\mathrm{amb}}^4 - T^4) \end{aligned}$$

Electrochemical model:

A secondary current distribution model of the electrolyte was constructed for the electrochemical corrosion model. The model considers the welded metal surface to be anode due to low corrosion potential among the metals and the base metal surface is taken to be cathode. The electrolyte is taken to be 3.5% NaCl solution as considered in experiment.

In any friction stir welding process, the process parameters affect the material properties of welded metal. Increase in rotational speed results in dynamic recrystallization and fine equiaxed grains, hence leading to increase in corrosion resistance. Also, increasing weld speed is accompanied by reduction in friction heat, which leads to decreased grain size.

The following assumptions are taken for the electrolyte solution within the secondary current distribution model:

1. Electrolyte solution is well mixed. There is no concentration gradient in the electrolyte solution.

2. The solvent is incompressible: divergent of velocity leads to zero.

3. The solution is electro-neutral.

4. Dissolution reaction takes place at the anode surface whereas hydrogen evolution reaction takes place at the cathode surface. Corrosion is assumed to be taking place only at the anodic surface and cathodic surface is non-corroding.

Governing Equation:

It is essential to identify the relationship between grain size and process parameters of FSP. In a study, an empirical relationship was established between process parameters and grain size to predict grain size of weld nugget zone, using statistical tools such as simple linear regression analysis. It is given as

$$\begin{split} (WG) &= 22.88 - 7.30(N) - 0.63(S) - 0.95(F) - 1.13(D) \\ &- 3.57(P) + 0.52(H) - 0.83(NS) - 0.77(NF) \\ &- 0.43(ND) + 1.13(NP) - 0.5(SF) - 1.0(SD) \\ &- 0.84(SP) - 0.65(SH) - 1.08(FD) - 0.58(FP) \\ &- 0.84(FH) - 0.58(DH) - 0.52(PH) + 4.10(N^2) \\ &+ 3.4(S^2) + 3.14(F^2) + 2.85(D^2) + 2.85(P^2) \\ &+ 3.95(H^2) \, \mu m \end{split}$$

Where N = Rotational speed(RPM), S = Welding speed(mm/min), F = Axial Force(kN), D = Diameter of shoulder(mm), P = Diameter of Pin(mm) and H – Vickers hardness number of base metals.

Predicting grain size is essential as it influences the corrosion current density and subsequently changes the corrosion. Once grain size has been deduced through the empirical relationship, it can be used to find corrosion current density.

Numerous experiments citing corrosion rates for different materials and environments have concluded that it was observed that as grain size decreases, corrosion current density increases. Decrease in grain size of a region results in increase in grain boundary area. As the energy of grain boundary is higher than that of grain, the total surface energy of the metal increases and corrosion current density increases. Studies have shown that the relationship between corrosion current density and grain size can be taken as a non-linear function.

The non-linear equation is established as below:

$$i_{\rm corr} = (A) + (B)gs^{-0.5}$$

where Icorr = Corrosion current density(A/cm²) and Gs = Grain size(um). Here, A is a function of environment and given grain size and B is material constant, subjected to change by material composition, which when divided by square root of grain size, gives the change in corrosion current density due to change in grain size.



Fig.3 Correlation between corrosion current density and grain size of Al

Once the corrosion current density of welded metal has been deduced, corrosion modelling was constructed.

Nernst-Planck equation is used to find out the transport of species (metallic ions and electrons) in electrolyte. It adds the species flux that takes place due to diffusion, migration, and convection of ion. It is given as:

$$N_i = -D \nabla c_i - z_i F u_i c_i \nabla \phi + c_i V$$

Where Ni is the flux, D is the diffusion coefficient, zi is the mobility of species, Ci is concentration, Ui is the charge, F is Faraday's constant (96500 C mol⁻¹), ϕ is electric potential and V is solvent velocity.

The conservation of species flux in electrolyte is defined by:

$$\frac{\partial c_i}{\partial t} = -\nabla \cdot \mathbf{N}_i = \mathbf{D}_i \nabla^2 \mathbf{c}_i - \mathbf{z}_i F \mathbf{u}_i \nabla \cdot (\mathbf{c}_i \nabla \phi) + \nabla \cdot (\mathbf{c}_i \mathbf{V})$$

As per the assumptions taken earlier, the species transport by convection and by diffusion are neglected. The physics can be simply reduced to solving the potential distribution as

$\nabla^2 \phi = 0$

This is the Laplace equation for electric potential in electrolyte. Solving this equation with the boundary conditions will give us potential and current density distribution at each node.

Boundary Conditions

The boundary conditions are important to predict corrosion rate. The boundary conditions at anode-electrolyte interface are given by

$$\nabla_n \phi = -\frac{f_a(\phi)}{\sigma}$$

Where σ refers to electrolyte conductivity and fa refers to anodic current density. Anodic current density is obtained by piecewise cubic interpolation of polarization data from the experiments.

And the boundary conditions at cathode-electrolyte interface is given by

$$\nabla_n \phi = -\frac{f_c(\phi)}{\sigma}$$

Where fc refers to cathodic current density. Cathodic current density is obtained by piecewise cubic interpolation of polarization data from the experiments.

The insulation boundary conditions surrounding the electrolyte solution is given by

$$\nabla_n \phi = 0$$

Current density and potential is obtained at different nodes of the weld metal by solving the Laplace equation with respect to the boundary conditions. Current density values are used to deduce corrosion rates through Faraday's Law.

The weld metal, or weld region metal, is taken to be anode due to lower corrosion potential and the base metal - Al is taken to be cathode due to higher corrosion potential.





Process Parameters:

The thermal properties of AA1100 such as melting point and heat coefficient were taken from predetermined data. Yield criteria of AA1100 is temperature dependent, hence experimental data was obtained and linear interpolation and constant extrapolation were performed to determine yield stress at different temperatures.

The material of tool pin is H13. The tool pin has a circular profile with tool pin with the radius of 2.5mm and tool shoulder with the radius of 8mm. The welding speed of the tool pin 100mm/min and its rotational speed is 1200 RPM. The axial force provided is 5kN and the friction coefficient is 0.3.

Electrochemical properties of AA1100 such as equilibrium potential and equilibrium current density were taken from predetermined data as well. The conductivity of 3.5% NaCl electrolyte solution is 7.2 S/m. The equilibrium potential and equilibrium current density of AA1100 base metal are 734 mV and 1.0679 A/m².

Process Parameter	Value
Welding speed (u_weld)	100 mm/min
Rotational speed (n)	1200 rpm
Radius of pin (r_pin)	2.5 mm
Radius of shoulder (r_shoulder)	8 mm
<i>Melting point temperature (T_melt)</i>	933 K
<i>Heat coefficient, upwards (h_upside)</i>	16 W/m ² K
Heat coefficient, downwards	$8.5 W/m^2K$
$(h_downside)$	
Friction coefficient (nu)	0.3
Axial Force (Fn)	5 kN

Table 1. Process parameters considered for the present study

Table 2.	Temperature-o	lependent yield	criteria of pure	aluminium	AA1100
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These 2. Temperature dependent fred enterna of pare distinguistics in the							
Temperature (°C)	371	316	260	204	149	100	24
Yield strength	11	14	18	24	29	32	34
(MPa)							

	A
Parameters	Value
Equilibirum potential, AA1100 base	-734 mV
metal (i0_cat1)	
Equilibirum current density, AA1100	$1.0679 A/m^2$
base metal (A_cat1)	
Electrolyte conductivity	7.2 S/m

Table 3. Parameters of electrochemical modelling of FSWed plates

CHAPTER 3

RESULTS AND DISCUSSION

Thermal modelling:

Thermal modelling of FSP was performed to find the surface temperature to observe how it correlates with the process parameters. The surface temperature observed in simulation were validated by experimental values as well. The maximum surface temperature observed around the pin should be 70-90% of melting point temperature of the material.





Fig.5. Surface Temperature for A)600 B)900 and C)1200 RPM

The simulation values of surface temperature were 162.72 C, 232.82 C and 301.68 C for the rotational speed of 600, 900 and 1200 RPM, showing a variation of 1.6-2.3% with respect to the experimental data.

Electrochemical modelling:

Two aluminium plates of dimensions $84 \times 38 \times 3$ mm were taken and its potential and current density distribution across the electrolyte 3.5% NaCl solution were simulated.

The results of the simulation are as follows:





Fig.6 Electrolyte potential distribution across electrolyte of FSP – AA1100 for N=900 RPM and N=1200 RPM

The electrolyte potential distribution for both N=900 RPM and N=1200 RPM lies between 0.680-0.700 V as indicated in the experimental data graph.





Fig.7 Corrosion rate vs Material coordinates diagram for FSP – AA1100 for N=900 RPM and N=1200 RPM

The corrosion rate of base metal in simulation were 1.97 mm/yr. and 1.675 mm/yr. for rotational speed of 900 and 1200 RPM. The simulation values varied from the experimental values with difference of 12-13%. The simulation also shows how corrosion rate varies along the welded region.

CHAPTER 4

CONCLUSIONS

The simulation model for corrosion of FSP was developed, which incorporated the microstructure modification during FSP by combining the coupled electrochemical modelling with a set of empirical relationships established in various studies. This enabled the simulation model to foresee the changes in material properties, such as corrosion current density, with respect to different process parameters of Friction Stir Processing and predict the corrosion rates of the welded region accordingly.

The experimental values and simulation values of temperature observed 1mm from shoulder point is as follows:

Rotational Speed	Experimental value	Simulation value of	Variation from
(RPM)	of Surface Surface Temperature		experimental
	Temperature (C)	(C)	value
600	166.7	162.72	-3.98(2.3%)
900	236.7	232.82	-3.88(1.6%)
1200	306.65	301.68	-4.97(1.6%)

Table 4: Experimental and simulation values of surface temperature.

The experimental values and the simulation values for various rotational speeds are as follows:

Table 5: Experimental and simulation values of corrosion rate.

Rotational Speed (RPM)	Experimental value of corrosion rate (mm/yr.)	Simulation value of corrosion rate (mm/yr.)	Variation from experimental data
900	2.24	1.97	+0.27(12%)
1200	1.925	1.675	-0.0038(12.98%)

Friction Stir Processing of 3mm AA1100 plates were performed, and a corrosion study was conducted in an experimental setup. The values obtained were used to validate the values observed in the simulation model, which indicated that the predicted values had a maximum error rate of 2.3% in thermal model and 12.98% in electrochemical model, indicating the accuracy of the model.

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