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Procedia Engineering 00 (2013) 000–000

Procedia Engineering

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Selected papers of Mechanical, Civil and Chemical Engineering tracks of the 4th Nirma University International Conference on Engineering (NUiCONE 2013)

Thermal Modeling of Immersed Friction Stir Welding of Aluminum Alloy

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Abstract

This study aims to experimentally see the thermal histories and temperature distributions in a workpiece during an immersed friction stir welding (FSW) process involving the butt joining of aluminium AA 8011 in water. K- Type thermocouples are used to compute the temperature histories for the period of FSW at different locations on the workpiece in the welding way. M-seal (epoxy compound) is used to prevent the contact of water to thermocouples. Regression analyses by the least squares method are used to forecast the temperatures at the joint line. A second-order polynomial curve is established to best fit the investigational temperature values in the width direction of the workpiece. A three-dimensional thermal model for Friction Stir Welding (FSW) is presented. The simulation model is tested with existing experimental results of aluminium alloys 8011.For immersed joint, the peak-temperature distributing region is significantly lessened and the welding thermal cycles in different zones are successfully controlled.

Keywords: *Keywords:- Friction stir welding, Finite element modelling, ANSYS*

Nomenclature

g	Gravitational force , m/s^2
t_s	Temperature of the surface, ^{0}C
t_w	Water temperature sufficiently far from the surface, ^{0}C
L	Characteristic length of the geometry, m (length/4 for flat surface)
k	Thermal conductivity W/m.K
R_{al}	Rayleigh number
Nu	Nusselt number
Pr	Prandtl number
C_p	Specific heat J/kg.K
β	Coefficient of volume expansion, 1/K
ρ	Density of fluid Kg/m^3
μ	Dynamic viscosity of the fluid, kg/m.s

1. Introduction

Friction Stir Welding (FSW) is a relatively new welding process, patented in 1991 by Thomas et al [1], [2]. A schematic diagram illustrating the process of FSW is shown in Fig. 1.1. The rotating tool is plunged vertically into the work piece, and, after a short pre-heating dwell, is traversed along the joint line, after which it is retracted vertically. The key components of

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E-mail address: er.anuppatel@gmail.com the FSW tool are material and geometry of shoulder and pin [3]. The Shoulder is the most important means of generating heat during the process, and it prevents material expulsion and assists material movement around the tool. The pin's primary function is to deform the material around the tool and its secondary function is to generate heat.

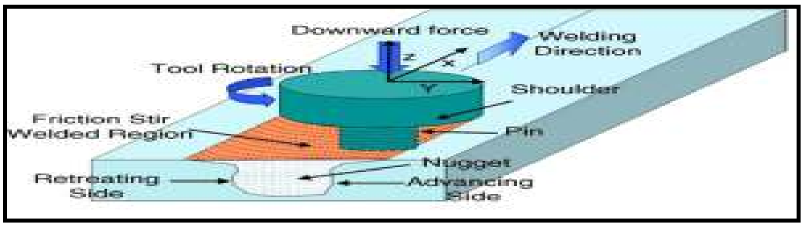


Fig 1.1 Schematic drawings of friction stir welding [3].

2. Literature Survey

Zhu et al. [4] developed Three- dimensional nonlinear thermal and thermo-mechanical numerical simulations are conducted for the friction stir welding (FSW) of 304L stainless steel. The finite element analysis code WELDSIM, developed by the authors specifically for welding simulation was used. Two welding cases with tool rotational speeds of 300 and 500rpm are analyzed. Chao et al. [5] formulate the heat transfer of the FSW process into two boundary value problems (BVP)—a steady state BVP for the tool and a transient BVP for the work piece. Two commercial finite element software – ABAQUS and WELDSIM – to simulation the heat transfer and fluid flow during friction stir welding process. The heat transfer model was formulated as a boundary value problem where the heat input was divided into 2 parts, the tool (Q_3) and the work-piece (Q_1). The authors reported that 95% of the heat produced through the friction between the tool and the work-piece flowed to the work-piece whereas only 5% dissipated to the tool. Frigaard et al. [6] developed numerical three-dimensional (3-D) heat flow model for friction stir welding (FSW) has been developed, based on the method of finite differences. The algorithm, which is implemented in MATLAB 5.2, is provided with a separate module for calculation of the microstructure evolution and the resulting hardness distribution. Colegroove et al. [7] used an advanced analytical estimation of the heat generation for tools with a threaded probe to estimate the heat generation distribution. The fraction of heat generated by the probe is estimated to be as high as 20%, which leads to the conclusion that the analytical estimated probe heat generation contribution is not negligible. Schmidt et al. [8] developed analytical model of heat generation in friction stir welding (FSW), based on different assumptions of the contact condition between the rotating tool surface and the weld piece. The material flow and heat generation are characterized by the contact conditions at the interface, and are described as sliding, sticking or partial sliding/sticking. Also this variable known as contact state variable ‘δ’ Hwang et al. [9] experimentally discover the thermal histories and temperature distributions in a workpiece during a friction stir welding (FSW) process involving the butt joining of aluminium 6061-T6. Different types of thermocouple arrangement are devised to measure the temperature histories during FSW at different locations on the workpiece in the welding way. Zhang et al. [10] conducted thermal modelling of underwater friction stir welding (FSW). FSW experiments were carried out to validate the calculated results, and the calculated results showed good agreement with the experimental results. The results indicate that the maximum peak temperature of underwater joint is significantly lower than that of normal joint. For underwater joint, the high-temperature distributing area is dramatically narrowed and the welding thermal cycles in different zones are successfully controlled in contrast to the normal joint.

3. Experimental Setup

This experiment deals with a butt weld single pass welded joints of two identical plates made of AA 8011 alloy. The FSW setup consists of 5mm thick plates, 50 mm wide and 150mm long. The tool is made of HSS tool-steel as shown in Fig.3.1, having shoulder diameter of 14mm. The pin has a height and diameter of 5mm and 4 mm respectively. Agilent data logger attached with k-type thermocouples for measuring the temperatures history in immersed FSW in water. The chemical composition and mechanical properties of the base material are presented in Table 3.2 and Table 3.1, respectively. The setup used for FSW is vertical milling machine which was mounted with an indigenously designed fixture fabricated from mild steel as shown in Fig. 3.1. The jig has clamping provisions to hold the plates firmly in the z direction. The set up shows rotation direction, moving direction of the tool and locations of thermocouples in the workpiece as mentioned in Fig. 3.2. The holes are drilled at the middle in the thickness direction of the work piece's edge side. The tip of the thermocouple is located as 4 mm, 6 mm, 8 mm and 10 mm away from the weld seam line in width direction and placed at distance on advancing side of the plate. All thermocouples are located in the heat affected zone. The temperature-time history plots are presented for the total time 120 second shown in Fig.3.3 The thermocouples cannot be placed at the stirring zone of tool pin.

M-seal (epoxy compound) is used to prevent the contact of water to thermocouples. FSW is performed at a rotation speed of 1400 rpm, downward force of 3.5kN and a welding speed of 63 mm/min to and an effective plunge depth of 4mm. At these values of the welding parameters, an adequate welding quality was obtained and the heat distributions were measured in the friction stir weldment of AA 8011 plate. Thermal history is shown in Fig 3.3

Table 3.1 MECHANICAL PROPERTIES OF AA8011 ALUMINIUM ALLOY

Tensile Strength Mpa	Density (kg/m^3)	Thermal Conductivity (W/m.k)	Melting Point (^{0}C)	Hardness HRB	Specific heat (J/Kg. ^{0}C)
110	2689	237	660.2	60	930

Table 3.2 CHEMICAL COMPOSITION OF AA8011 ALUMINIUM ALLOY

Fe	Si	Mn	Mg	Zn	Cu	Ti	Cr	Al
0.74	0.52	0.459	0.277.	0.084	0.127	0.016	0.028	Rem.

Fig 3.1 Assembly of fixture and Data logger

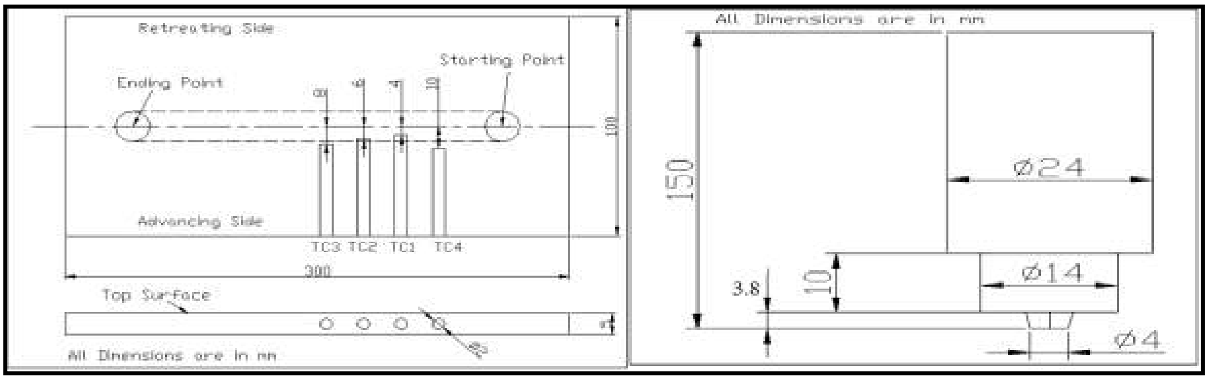


Fig 3.2 Thermocouple layout and tool geometry

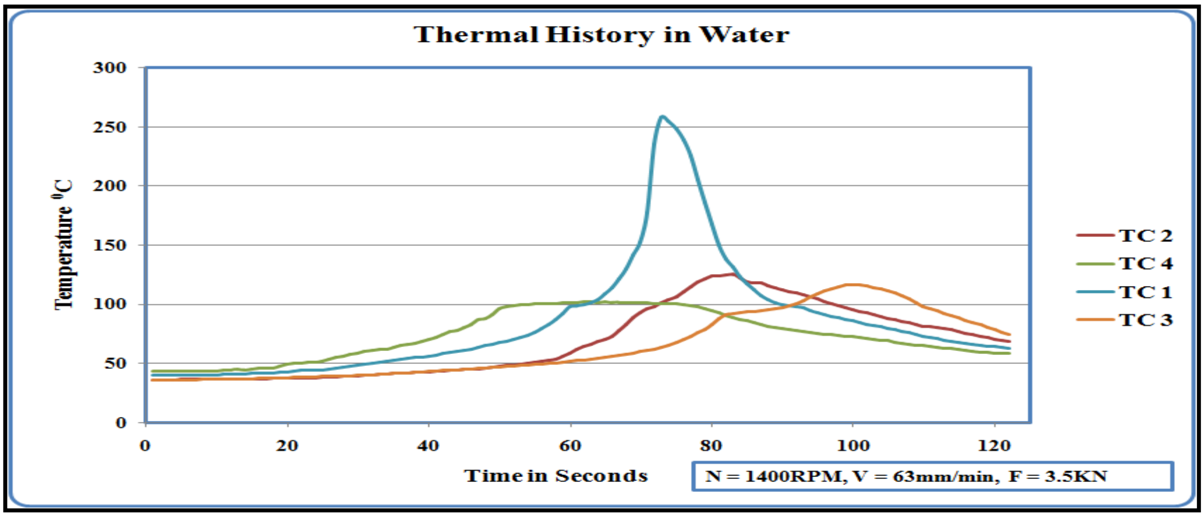


Fig 3.3 Measured temperature-time variations at various monitoring locations

4. Regression analysis for temperature distributions in the width direction

Illustrate the temperature distribution in the width path of the workpiece using one linear and two second-order equation to, as stated below $T = x_1 + x_2d$, $T = x_3 + x_4d^2$ and $T = x_5 + x_6d + x_7d^2$ where T is the temperature at a point with a distance d from the joint line, and parameters x1–x7 are resolute by least squares method [12]. Only four temperature values from the thermocouples in the width direction are used. The maximum value of the temperature contour start at d = 2 mm, which the radius of the tool pin of 2 mm. The temperatures inside the tool pin can be regarded as homogeneously distributed, and the heat transfer starts from the rim of the tool pin. Regression analysis detailed shown in Table 4.1 and Fig. 4.1 for temperature prediction

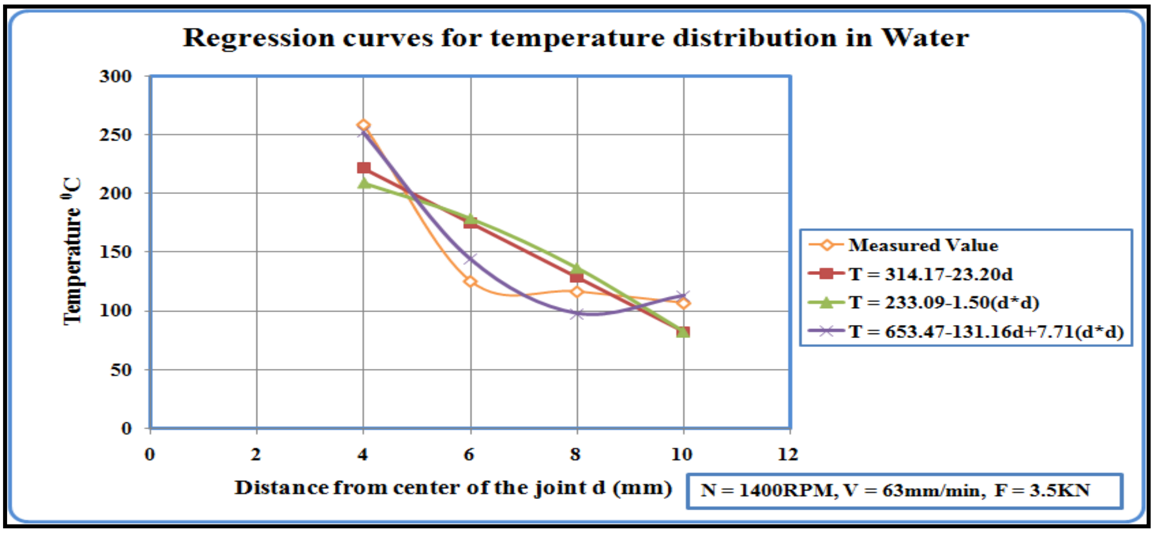


Fig 4.1 Regression curve for temperature distribution in width direction

Table 4.1 Regression analysis for temperature prediction at the joint line

Measured Temperature		258.445	125.265	116.45	106.653	Predicted Temperature At joint line (°C)
$T = a_1 + a_2d$	Regression value	221.33	174.91	128.49	82.07	267.75
$T = a_3 + a_4d^2$	Regression value	208.98	178.83	136.63	82.37	227.07
$T = a_5 + a_6d + a_7d^2$	Regression value	252.18	144.07	97.65	112.92	421.98

5. Thermal Modeling of friction stir welding

The purpose of the thermal model is to compute the transient temperature fields developed in the work piece 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)

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q_i = C\rho\frac{\partial T}{\partial t} \tag{1}$$

Where k is the coefficient of thermal conductivity, Q_i is the internal heat source rate, C is the mass-specific heat capacity, and ρ is the density of the materials [4]. A solid70 and surf152 element used for transient temperature analysis in ANSYS. Calculated heat flux and natural convection applied as a boundary condition.

5.1 Calculation of Heat flux and Natural convection

Calculation of natural convection calculated using below procedure. Temperature of surface was 421.97 ^{0}C and Temperature of air was 25 ^{0}C. Properties of water at temperature [11] 223.485 ^{0}C, Pr = 0.88, k = 0.646, L = 0.075, C_p = 4.585, μ = 1.20.

$$t_f = \frac{421.97+25}{2} = 223.485, \beta = \frac{1}{t_f+273}, R_{al} = \frac{g\rho^2\beta C_p(t_s-t_a)L^3\,\mathrm{Pr}}{\mu\kappa}, Nu\ = 0.54(R_{al})^{1/4}, h = \frac{Nu\times\kappa}{L} = 59.09 w/m^{20}C$$

Heat flux can be calculated using tool geometry and parameter used for friction stir welding. The procedures are as follow.

$$Q_s = \frac{2}{3}\frac{\pi\mu P\omega(R_o^3 - R_i^3)}{(R_o^2 - R_i^2)} \tag{2}$$

Heat flux generated by tool shoulders Q_s can be calculated using above equation [6] where R_o = 0.007, R_i = 0.002, μ = 0.2 and Schmidt et al. [8] recommended that ratio of heat generated from the tool pin Q_p and the heat generated from the tool shoulder Q_s was 0.128. The workpiece 300×100×5 mm was modelled by finite element software ANSYS shown in fig 5.1 . A calculated natural convection between aluminium and water a convective heat transfer coefficient 60 W/m^2 °C used to all surfaces except the bottom surface of workpiece. The work pieces were clamped over Asbestos plates. A heat transfer will be zero to the bottom surface of the workpiece. A coordinate system was moved after each load step. At every load step a set of elements in the shape of the tool are selected. Calculated total heat flux using equation (2) was applied on the surfaces of the elements. The results of the simulation are in good agreement with that of experimental investigational results for the temperature in transverse direction as shown in fig.5.2.

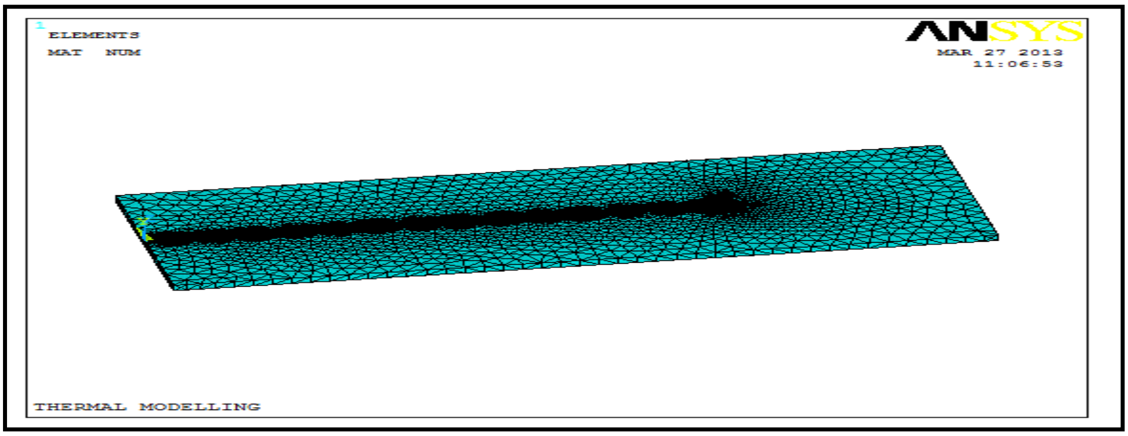
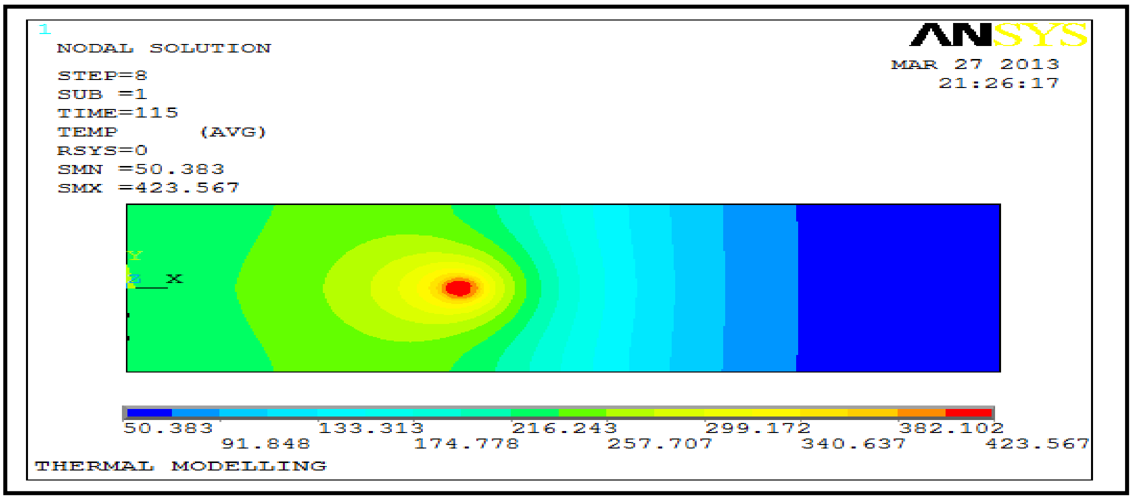


Fig.5.1 Meshing of FSW workpiece



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NODAL SOLUTION

STEP=8
SUB =1
TIME=115
TEMP       (AVG)
RSYS=0
SMN =50.383
SMX =423.567
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Fig 5.2 Temperature distribution on top surface of the workpiece

6. Conclusion

1. A thermal model simulation is carried out to predict the peak temperature during friction stir welding of AA 8011 aluminium alloys and this model is validated through experimental results. The peak temperature obtained was 421.97 ^{0}C using regression analysis and 423.597 ^{0}C using simulation.
2. The maximum peak temperature of immersed joint is still considerably lower than that of normal joint due to the severe heat absorption capacity of water.

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