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Simulating ultrasonic vibration enhanced FSW process of AA6082 using finite element method

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Abstract. Several modifications have been made on friction stir welding process to overcome some certainlimitations which have been reported. One of these modifications is to use ultrasonic energy as an assistance tool in FSW process. In the present paper, a mathematical model is developed to express the heat generation during ultrasonic vibration enhanced friction stir welding process (UVeFSW). A finite element model is built to perform a transient thermal heat transfer analysis using ANSYS mechanical APDL software package. The temperature contours, temperature distribution and the thermal cycles were predicted using the moving heat source technique. To validate the model, k-type thermocouples were used to measure the temperature and thermal cycles at five locations. The results showed a good agreement between the simulated and experimentally measured results.

1. Introduction

Friction stir welding process (FSW) is considered to be one of the most advances in welding technology. As a solid-state welding technique, FSW has many advantages over fusion welding processes,as it consumes less energy, no fumes or gases are emitted during the process, no fillers or fluxes are needed making the process, energy efficient and environmentally friendly, in addition to low distortions and residual stresses.FSW process has been used successfully to weld a wide range of soft materials such as Al and Mg alloys. It has achieved acceptable level of weld quality and joint properties. Now days, many attempts are made to widen the range of materials that can be welded using FSW to include harder aluminium alloys, high strength, and high melting point materials. Such hard materials necessitate more amount of frictional heat to achieve sufficient degree of material plasticization at the weld zone. This requires low welding speed, high downward force and high spindle torque. Such requirements represent some limitations in friction stir welding of hard materials.

To overcome these limitations, the researchers have proposed to integrate FSW process with an auxiliary energy source to provide additional energy. Thermal and mechanical sources were used to obtain this required energy. The thermal means include laser assisted FSW[1], arc assisted FSW[2] and electrically assisted FSW[3]. On the other hand, the mechanical source includes only ultrasonic vibration assisted FSW.Compared to other auxiliary energy sources, ultrasonic energy has many advantages as it helps in enhancing the material flow as it produces finer grains size, improving the mechanical properties of the joint, consumes less energy, simple and more save than other processes[4]. Ultrasonic vibration can be integrated with FSW by two techniques, the first is to apply

the waves to the tool which transmit the vibration to the weld area and it is known as ultrasonic vibration assisted FSW (UAFSW)[5]. The second is to apply the waves directly to the workpiece and it is known as ultrasonic vibration enhanced FSW (UVeFSW) as invented by Lai et al. in 2015[6]. The mechanism of FSW process and its related modifications depends basically on the heat generated during the process. many properties of the resulting joints are affected by the thermal behaviour of the material. one of the most useful approaches to study this behaviour isthe finite element modelling. Several models have been developed to simulate the heat transfer in conventional FSW. Choetal. analysed the heat transfer in FSW using computational fluid dynamics approach[7]. Heetal, predicted the temperature distribution in FSW by developing a thermo-mechanical model[8]. A finite element model was developed by buffa et al. to investigate the influence of process parameters on temperature distribution[9]. On the other hand, there are few researches that investigated the heat transfer in ultrasonic vibration assisted FSW using finite element method. The additive inertial force exerted by ultrasonic vibration of the tool in UAFSW process was considered in the model developed by Lai et al. to analyze the effect of ultrasonic vibration on thermal process[10].A mathematical model was developed by Shi et al. to investigate the effect of ultrasonic vibration on the heat generated during UVeFSW process[11].

There is still a shortage in developing a finite element model to simulate UVeFSW process. The objective of the present work is to develop a clear mathematical model to calculate the heat generation rate and heat flux as well as developing a finite element model to predict the temperature distribution and thermal cycles resulting from UVeFSW process.

2. Mathematical model

The heat generated during FSW process has a significant influence on the success of the process as it affects the weld quality, microstructure and the amount of residual stresses and distortions. In general, there are two main sources for heat generation in FSW process including the frictional heating at the contacting interfaces of the tool and the workpiece in addition to the heat generated due to plastic deformation of the material at the stirring zone.

An expression was introduced by Schmidt et al.to estimate the heat generation rate at the tool/workpiece contact interface, equation (1)[12]:

$$q(r) = [\eta(1-\delta)\tau_c + \delta\mu P_N](\omega r^2) \tag{1}$$

Where, $q(r)$ is heat generation rate, δ is the dimension slip rate, η is the mechanical efficiency, τ_c is the contact shear stress, μ is coefficient of friction, P_N is the normal pressure of the tool over the workpiece surface, ω is the rotational speed of the tool, and r is the distance between the elemental area and the tool axis.

The heat generated at the tool shoulder/workpiece contact surface is obtained by integrating equation(1) over the surface of the tool shoulder as follows in equation(2):

$$Q = \int_{R_P}^{R_s} \int_0^{2\pi} [\eta(1-\delta)\tau_c + \delta\mu P_N](\omega r^2)d\theta dr \tag{2}$$

whereR_s and R_P are the radius of the tool shoulder and the tool pin respectively.Based on von-Mises criteria, the contact shear stress during the UVeFSW process can be determined from the following equations(3), (4), (5):

$$\tau_c = \frac{\sigma_{yo}}{\sqrt{3}} \tag{3}$$

Where, σ_{yo} is the yield stress of the material without the influence of ultrasonic vibration. To consider the effect of the ultrasonic vibration on the yield stress of the material a model was proposed by Kelly et.al[14]:

$$\sigma_{yo} = K\varepsilon_p^n \tag{4}$$

$$\sigma_y = \xi K\varepsilon_p^n \tag{5}$$

Where, ξ is the percentage of acoustic softening, the value of ξ ranges from zero to one. At $\xi = 1$ there is no acoustic softening and the material will deform normally. At $\xi = 0$ the acoustic softening is sufficient to reduce the yield stress of the material to zero (a theoretical case).The percentage of acoustic softening can be predicted depending on the ultrasonic vibration parameters through the following equation (6):[14]:

$$\xi = 0.177 + \frac{1.74}{1 + \exp(0.109 + 171\Lambda - 47.0\Lambda P_s)} \tag{6}$$

Where, P_s is the dimensionless pressure and Λ is the dimensionless amplitude and is given byequation (7):

$$\Lambda = \frac{\lambda}{t} \tag{7}$$

Where, λ is the ultrasonic vibration amplitude, and t is the workpiece thickness. The dimensionless pressure (P_s) is given byequation (8):

$$P_s = \frac{P_h}{\sigma_{yo}} = \frac{F_h}{\pi R_h^2 \sigma_{yo}} \tag{8}$$

Where, P_h is the pressure of the sonotrode on the workpiece, F_h is the clamping force of the sonotrode, R_h is the radius of the sonotrode.By substituting in equation (2), the final equation to estimate the heat generation due to friction between the tool shoulder and the plastic deformation of the material can be expressed as followingequation (9):

$$Q = \frac{2}{3}\pi \left[\eta(1-\delta)\frac{\xi\sigma_{yo}}{\sqrt{3}} + \delta\mu P_N \right](R_s^3 - R_P^3)\omega \tag{9}$$

3. Finite element modelling
The heat generated from the tool surface is transferred into the workpiece according to the Fourier's law of heat conduction [15]. The heat transfer equation is as the followingequation (10):

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) \tag{10}$$

Where ρ is the material density, T is the absolute temperature, C_p is the specific heat, $K_x, K_y,$ and K_z are the heat conductivitiesthat vary with temperature. The transient thermal analysis model is based on a moving heat source which is generated by the frictional heating and the plastic deformation of the material. The material used in this simulation is AA6082-T6. One half of the parts to be welded is modelled assuming symmetry about the weld line to reduce simulation time. The part dimensions are $160 \times 100 \times 3\ mm$. Defining the material properties properly plays a dominant role in obtaining more accurate results. The temperature dependent properties of

AA6082-T6 are listed in table (1) [16]. Since the material density is little affected by the temperature variation, a constant value of **2710 kg/m^3** is defined.

Table 1.The material temperature dependent properties of AA6082.

Temperature (°C)	Conductivity (w/m °C)	Specific heat (j/kg °C)
20	179.1	870
100	194.6	934
200	205.2	967
300	209.8	1002
400	211.6	1066
500	225.3	1167

3.1. Meshing and Boundary conditions
The element type used in the present model to mesh the workpiece is a brick element called SOLID 70. The element has 8-nodes with temperature as a single degree of freedom at each node.The boundary conditions applied for the present thermal model are the conductive and radiative heat losses from all free workpiece surfaces to the surrounding except the bottom surface were conductive heat loss is only presented. The ambient temperature is 25°C. A convection coefficient of 30 W/m^2°C is applied for top and side surfaces and 300 W/m^2°C[15] is applied to the bottom surface of the workpiece as shown in figure 1.
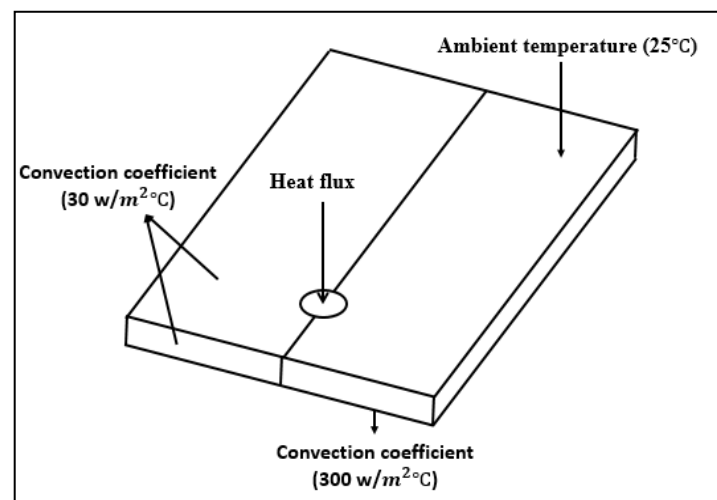

Figure 1.The boundary conditions defined in the model.

3.2. Heat flux
In the present thermal model, the heat generated during the UVeFSW process is simulated as a moving thermal heat flux, which is applied as a surface load. The heat flux is calculated as the following:

$$heat\ flux = \frac{heat\ input(Q)}{Area} \tag{11}$$

The mechanical efficiency ($\boldsymbol{\eta}$) is taken equal to 0.9 according to Awang[17], the dimension-less slip rate ($\boldsymbol{\delta}$) calculations is discussed in details in the study made by Hamilton [18]. the yield stress of the

material approximately approaches **60 MPa**at**400** °C[19].The coefficient of friction (**μ**)is taken to be 0.4.

$axial\ force\ (F) = 3000\ N$

$P_N = \frac{F}{A}$where: A is the area

$R_s = 7\ mm$and$R_p = 2.5\ mm$

$A = \pi\left(R_s^2 - R_P^2\right)$

$\omega = \frac{2\pi N}{60}$ N: is the tool rotational speed (**rpm**)

$heat\ flux = 3.2 \times 10^6$

4. Experimental work

4.1. Material and welding procedure

The material to be welded is AA6082-T6 which is a promising alloy as it has the highest strength value of all 6000 series aluminium alloys. The chemical composition as provided by the supplier is shown in table (2). The specimen dimensions are ($160 \times 100 \times 3\ mm$). A conventional milling machine was used to perform the welding operation. The process parameters utilized were a rotational speed of 800 rpm, a welding speed of 80 mm/min, tilt angle of 2° and plunge depth of 0.15 mm. an FSW tool of 14 mm shoulder diameter, a pin diameter of 5 mm and a pin length of 2.7 mm.

An ultrasonic processor (model up 400S) manufactured by (Hielscherultrasonics GmbH) was used to obtain the required ultrasonic vibration. Ultrasonic vibration waves of a frequency of 20 KHz, a power of 85 watt and amplitude of 40 μmwere employed. The ultrasonic processor was attached to the head of the milling machine via a suitable attachment. so that, the sonotrode can move along the welding line ahead of the FSW tool by a distance of 30 mm and with inclination angle between the axis of the sonotrode and the workpiece surface of 60°to keep it away from the tool. Thereby, the ultrasonic vibration waves can be transmitted directly into the localized area of the workpiece without any loss in the transmitted energy compared to other methods for transmitting the ultrasonic vibrations as shown in figure 2.

Figure 2. Experimental setups of ultrasonic vibration friction stir welding process.

Table 2. Chemical composition of AA6082

Si	Fe	Cu	Mn	Mg	Cr	Ni	Ti	Al
0.7-1.3	0.5	0.1	0.4-1.0	0.6-1.2	0.25	0.2	0.1	REM

4.2. Temperature measurement

The temperature was measured during the welding process on the advancing side using K-type thermocouple at five locations (P1, P2, P3, P4. and P5) at a depth of 2 mm from the top surface as shown in figure (3). In order to monitor the temperature with time an Arduino circuit consisting of

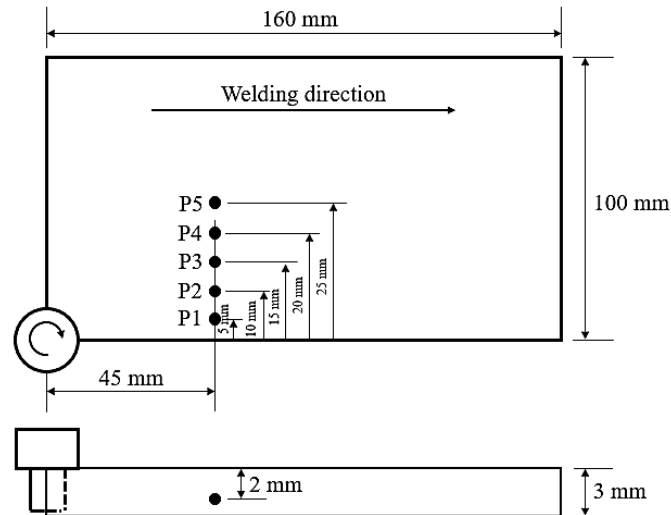Arduino board mega 2560, module MAX 6675 to amplify the signal and the temperature sensor was utilized.

Figure 3.Locations of thermocouples in the workpiece.

5. Results and discussion
As building the finite element model and applying various loads such as calculated heat flux and convection coefficient has been accomplished, the transient heat transfer analysis is performed. After the solution of the model has been completed, three types of data can be obtained which are necessary from point of view.

5.1. Temperature contours
The moving heat source is simulated successfully in the present model as shown in figure 4. The red area represents the location of the moving heat source (location of the FSW tool). The temperature distribution over the welded workpiece is represented. At the first step a peak temperature of 388 C$^{\circ}$ is obtained which is increased to 396 C$^{\circ}$ in the second step. This increase may be attributed to the pre-heating effect of the former step on the later step.

(a)   Step 1

(b)   Step 2

(c)   Step 3
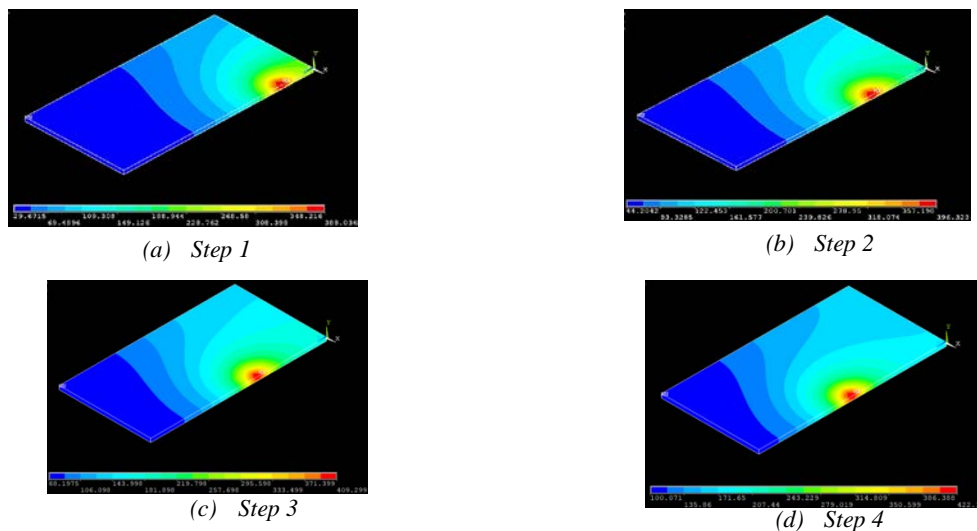

(d)   Step 4

Figure 4. Temperature contours at various steps.

5.2. Peak temperatures at different locations

Simulated and experimentally measured values of the peak temperatures at five different locations from the weld center line (P1=5, P2=10, P3=15, P4=20 and P5=25 mm) are represented at figure 5 to compare the results and hence determining the model accuracy and percentage error (error %) between simulated and experimentally measured data. As shown from the figure, the error% at P1 is about 3.27% and reaches the maximum value at P3 where error% is 6.14%. It is obvious from the results that the predicted results are in good agreement with the experimentally measured ones.
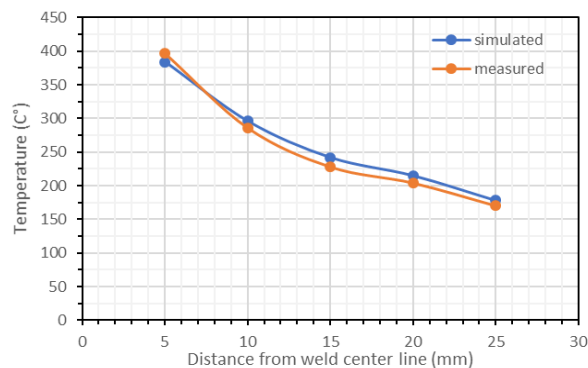

Figure 5. *Comparison between simulated and measured peak temperature at each location*

5.3. Thermal cycles

The variation of temperature with time (thermal cycles) has an important effect on the microstructure as well as the mechanical properties of the welded joints thus the thermal cycles at locations P1 and P2 were determined experimentally and predicted by the model. Also, the comparison between them at each location is shown in figure (6a,b). As the seen in figure 6a,b, it was observed that the variations between predicted and measured results are in the allowed limits.
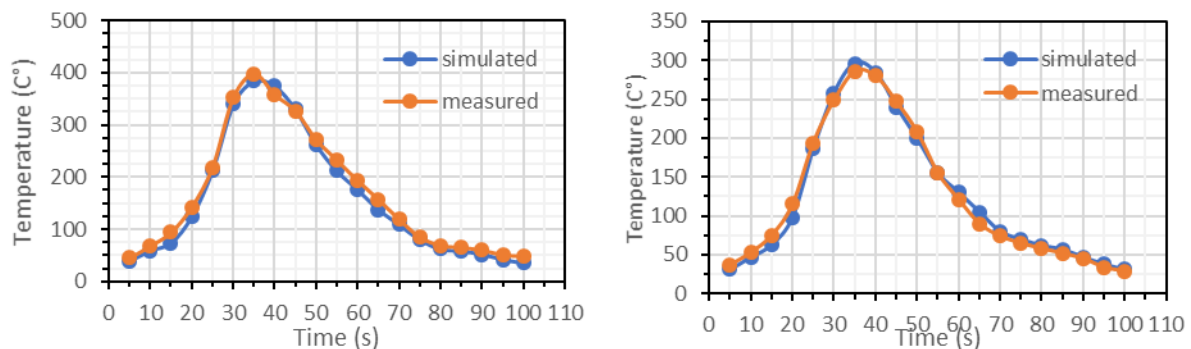

Figure 6.The thermal cycle at locations A) location P1, B) Location P2.

6. Conclusions

In the present study a transient heat transfer analysis was performed using finite element method. The moving heat source technique was applied to simulate the welding process. Temperature contours, temperature distribution and thermal cycles was predicted using ANSYS mechanical APDL software. The model was validated by measuring the temperature and thermal cycles using K-type thermocouple. The comparison between simulated and measured results showed acceptable accuracy of the model.

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