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Thermo Mechanical Modelling of Friction Welding using Finite Element Method (FEM)

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ABSTRACT

Friction welding is a complex process that involves material, thermal, physical and chemical changes. To understand this process better, modeling plays an important role. Thermal modeling of the process has been carried out extensively by many of the previous researchers. But only few of the researchers address the thermo-mechanical phenomenon involved in the friction welding process since thermo-mechanical modeling is more complicated. In the present work, a finite element based model is proposed including thermo-mechanical phenomenon using finite element method.

Key words: Friction Welding, Thermo Mechanical Modeling, Finite Element Method

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INTRODUCTION

Friction welding is a solid state joining process that uses rotational motion and high axial pressure to convert rotational energy into frictional heat at circular interface. The basic principle of friction welding is one of the components being welded is rotated while the other is kept stationary. The typical applications of friction welding include aircraft and aerospace components, drill bits, agricultural machinery, automotive parts, oil field pieces, military equipment, axle shafts, transmission shafts etc. Besides, friction welding is used for making joints with dissimilar material combination such as aluminium/steel, aluminium/copper, titanium/steel etc. [1]. Recently experimental works on joining of aluminium with steel are gaining importance due to their demand for diversified engineering applications. [2-3].

LITERATURE SURVEY

Since the late 1960s, thermal modelling has been a central part of the modelling of friction welding in general Vairis et al [4] simulated linear friction welding of titanium bars. Analytical model was developed and Vairis predicted the temperature rise in the initial phase of the process. In order to retain a certain degree of predictive ability in his model, it was assumed that at the beginning of the motion the two specimens are resting on asperities at the interface. The asperities are deforming predominantly in a plastic fashion under the normal load applied, as the contact is between rough metal surfaces. The developed a model to predict temperature evolution, stress, strain and final geometry of inertia Friction-welded similar parts. Using Finite Element-based software DEFORM, coupled deformation and heat flow analyses were carried out. His model was based on non-steady equation of the heat conduction with varying thermal properties in the coupled thermo-mechanical problem. His numerical results had a good agreement with the experimental values.

Sahin [5] introduced a friction subroutine in his visual basic program to model the shape of the upset in the continuous friction welding process. The transient three-dimensional temperature distribution in a continuous drive friction welding process of two concentric cylindrical bars was investigated numerically by him. A finite difference technique is used to obtain the solution for the above problem within a desired accuracy. Temperature rise at the interface plane was computed and related to the weld properties.

Recently, Seli et al [9] in their study evaluated mechanical properties of mild steel and aluminium-welded rods to understand the thermal effects. An explicit one-dimensional numerical model was developed using finite difference method to approximate the heating and cooling temperature distribution of the joint. But in their study, heat generation due to plastic deformation and heat loss by radiation to the environment were neglected for simplicity of the model.

Rajesh et al [6] carried out finite element based thermal analysis for friction stud welding of aluminium and mild steel, and ceramics/metal combination [7]. In a similar work, Rajesh et al [14] predicted thermal distribution and heat flow using finite element based software. But structural aspects were not considered in their works.
In the present work, a mathematical model for friction welding process has been developed including thermal and mechanical aspects using finite element method.

MATHEMATICAL MODELING

Friction welding is purely based on the heat energy obtained at the interface of the components due to rubbing action. Determination of heat flux at the interface is crucial step in modelling of the process. Besides, temperature distribution determines the quality and strength of the joints. Hence, both the aspects are included in the present model.

Heat Generation

The unsteady heat flow is expressed in the analyzed domain by the following two dimensions axisymmetric nonlinear heat transfer equation [11].

$$\rho\, c_p(\obslash)\ \partial(\obslash)/\partial(t)=\partial/\partial r(k(\obslash)\partial(\obslash)/\partial r)+k(\obslash)/r\ (\partial\obslash/\partial r)+\partial/\partial z(k(\obslash)\partial\obslash/\partial z)+q \quad (r,z)€\Omega \tag{1}$$

Where $k(\obslash)$ is the thermal conductivity and $c_p(\obslash)$ is the specific heat capacity, these two thermal property parameters vary with temperature.$\obslash$ is the temperature, r is radius and t is time. The expression q is

$$q= \alpha\varepsilon\sigma+q_i \tag{2}$$

Where $\alpha\varepsilon\sigma$ is the coupling factor for the thermo mechanical action and the rate of internal heat generation during the plastic deformation, α is the thermal efficiency of plastic deformation, σ is stress, ε is strain and q_i is the internal heat source.
The calculation model for the stress and strain fields of the welding process is described by Kirchhoff balance equation [6]

$$\int_{vo} S_{ij}\ \delta E_{ij}\ dV=\int_{vo} P_{oi}\ u_j\ dv + \int_{soT} T_{oi}\ \delta uj\ ds \tag{3}$$

Where S_{ij} is the Kirchhoff stress tensor, δE_{ij} is the Green Strain tensor, δuj is the component of virtual displacement and P_{oi} and T_{oi} are the unit volume force components acting on the deformed body respectively.
The nonlinear governing equation group can be obtained when the above two models are dispersed through the finite element method,

$$k_1(\obslash)u=f$$

$$c_p(\obslash)\pi+ k_1(\obslash)\obslash=Q \tag{4}$$

Where $k_1(\obslash)$ is the tangential stiffness matrix, u is the displacement incremental, f is the force vector. Q is the heat flux vector; $\obslash$ and π are nodal temperature vector and nodal temperature rate vector respectively.

Applying Boundary Conditions

The initial temperature in the welding parts is uniform and is described as

$$\obslash_{(t=0)} =\obslash_0 \tag{5}$$

On the free surface, the boundary condition is given as follows

$$k(\obslash)\partial \obslash/\partial n_{('I1)}=0 \tag{6}$$

and

$$k(\obslash)\partial \obslash/\partial n_{('I2)}=-(j_1+j_2)(\obslash-\obslash_s) \tag{7}$$

Where j_1 is the heat convection coefficient and j_2 is the heat radiation coefficient, $\obslash_s$ is the surrounding temperature.
On the friction surface, the boundary condition is written in the form of the following equation,

$$k(\obslash)\partial \obslash/\partial n_{('I3)}=-q(r,\obslash) \tag{8}$$

Where $q(r,\obslash)$ is the heat flux at the friction surface and is described as

$$q(r,\obslash)=2\pi r.\varsigma(r,t).p(r,t).\omega(t) \tag{9}$$

Thermo Mechanical Model

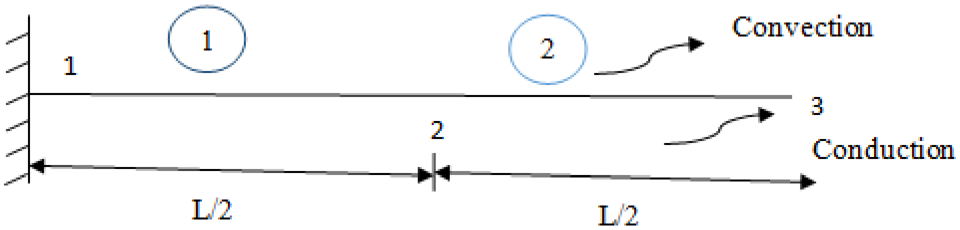

Fig .1 Schematic representation of Finite Element Model

Global Stiffness Matrix

Element 1: For the structural element

$$[K_1]=AE/\,(l/2)\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \tag{10}$$

Element 2: Heat conduction part of the stiffness matrix for the 1D is,

$$[K_c]=AK/\,(l/2)\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \tag{11}$$

Heat convection part of the stiffness matrix,

$$[K_h] \;= \iint_s h[N]^T[N]ds$$

$$[K_h] \;= hp\int_o^{l/2} [N]^T[N]\, dx \qquad\qquad (ds=p\ dx)$$

$$[K_h]=hp\int_o^{l/2}\begin{Bmatrix}((\frac{l}{2})-x)/(l/2)\\ x/(l/2)\end{Bmatrix}\begin{Bmatrix}((\frac{l}{2})-x)/(l/2) & x/(l/2)\end{Bmatrix} dx$$

$$[K_h] = hp\int_o^{l/2}\begin{Bmatrix}((\frac{l}{2})-x)/(l/2)2 & \frac{(\frac{l}{2})-x}{\frac{l}{2}}*x/(l/2)\\ \frac{x}{\frac{l}{2}}*\frac{(\frac{l}{2})-x}{\frac{l}{2}} & x2/(l2/4)\end{Bmatrix} dx$$

$$[K_h]= \;=hp\begin{bmatrix}l/6 & l/12\\ l/12 & l/6\end{bmatrix}$$

$$[K_h]=hpl/6\begin{bmatrix}1 & 1/2\\ 1/2 & 1\end{bmatrix} \tag{12}$$

Global stiffness matrix,

$$[K]= AE/\,(l/2)\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}+ hpl/6\begin{bmatrix}1 & 1/2\\ 1/2 & 1\end{bmatrix}+ AK/\,(l/2)\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \tag{13}$$

Global Force Matrix

Force matrix due to heat generation,

$$\{F_Q\} = \iiint_V [N]^T\, Q\, dv$$

$$\{F_Q\} = \int_o^{l/2} [N]^T\, Q\, A\, dx \quad (dv=A\ dx)$$

$$\{F_Q\} =QA\int_o^{l/2}\begin{Bmatrix}((\frac{l}{2})-x)/(l/2)\\ x/(l/2)\end{Bmatrix} dx$$

$$\{F_Q\} = QA\begin{Bmatrix}l/4\\ l/4\end{Bmatrix}$$

$$\{F_Q\} = (QAl)/4\begin{Bmatrix}1\\ 1\end{Bmatrix} \tag{14}$$

Force matrix due to convection,

$$\{F_h\} = \iint_s hT_0\, [N]^T\, ds$$

$$\{F_h\} =\iint_s hT_0\, [N]^T\, p\, dx$$

$$\{F_h\} = ph\, T_0\int_o^{l/2} [N]^T\, dx$$

$$\{F_h\} = ph\, T_0\int_o^{l/2}\begin{Bmatrix}((\frac{l}{2})-x)/(l/2)\\ x/(l/2)\end{Bmatrix} dx$$

$$\{F_h\} = ph\, T_0\begin{Bmatrix}l/4\\ l/4\end{Bmatrix}$$

$$\{F_h\}= (phT_0l)/4\begin{Bmatrix}1\\ 1\end{Bmatrix} \tag{15}$$

For the structural element,

$$\{F_s\}=\begin{Bmatrix}u1\\ u2\end{Bmatrix}[K] \tag{16}$$

One dimensional equation,

$$AE/(l/2)\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}\begin{Bmatrix}u1\\ u2\end{Bmatrix}+hpl/6\begin{bmatrix}1 & 1/2\\ 1/2 & 1\end{bmatrix}+AK/(l/2)\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}=\begin{Bmatrix}F1\\ F2\end{Bmatrix}+(QAl+phT_0l)/4\begin{Bmatrix}1\\ 1\end{Bmatrix} \tag{17}$$

Equation (17) gives the deformation of the components during the friction welding process. Thus the burn off due to thermo-mechanical phenomenon could be predicted by the model.

CONCLUSION

In the present work, thermo-mechanical model of friction welding process has been developed using finite element method. This method is more significant than the finite difference method since thermal and structural aspects are coupled. The developed mathematical model could be extended further to predict the temperature distribution and axial shortening distance during the friction welding process.

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