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Finite Element Analysis of Heat Transfer in Arc Welded Plate

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Abstract—*Welding is a very complex phenomenon. Therefore, it is necessary to develop practical models for the process, for which temperature distribution can be calculated within acceptable tolerance. This study is focused on the modeling and simulation of semi-automatic arc welding process to join mild steel plates in butt joint configuration. The model considers temperature dependent material property, melting, solidification and phase change. The current model predicts temperature distribution in the welding. Weld pool boundary is also obtained from this model.*

Keywords*: Arc welding; Mild steel; Heat transfer; Weld pool.*

1. INTRODUCTION

In fusion welding, a weld part is locally exposed to rapid heating. Thus, non-uniform temperature distribution occurs in the welded part. Solidification of the weld metal, metallurgical transformations, and thermo-plastic deformations result in residual stresses and distortions in the weld part. Welding is a very complex phenomenon. Therefore, it is necessary to develop practical models for the process, for which temperature distribution and the residual stresses can be calculated within acceptable tolerance. More than seven decades back, there was the first attempt to predict transient temperature distribution in welded plate was reported. After that, many research works have been reported in this area. However, accuracy in guessing of transient temperature distribution of the welded plate is still an important issue. Welding process involves variable thermo-physical properties of welded plate, fluid flow, convective and radiation heat loose, solidification etc. along with complex boundary conditions. All these cannot be included in an analytical solution. In such cases, sufficiently accurate approximate solutions can be obtained by computers using numerical methods. Nowadays, it is a popular practice of predicting temperature distribution of welded plates using various numerical methods.

Goldak *et al*. [1, 2] introduced the finite element model to predict the temperature of the welded joints. 3D double ellipsoidal moving heat source was assumed. The model overcame the shortcoming of the previous 2D Gaussian model.

Bag *et al.* [3] also predicted temperature profile through numerical method. They assumed an improved approach of a volumetric ellipsoidal heat source with appropriate heat source parameters. This numerical model was quite accurate for measuring the weld pool dimension. Biswas *et al.* [4] considered a numerical model based on the finite element package for single pass single sides submerged arc welding of square butt joints. Using it, they determined the distortion of welded joint. In their study, heat losses through convective losses were considered, however, radiative heat losses were not taken into account. Nart and Celik [5] proposed an approach to find temperature distribution in the pool. They also calculated residual stresses in fusion zone as accurate as possible results in more accurate fatigue life predictions of welded constructions.

In present work, transient temperature distribution of welded plate was predicted considering Gaussian heat source shape, convective and radiative heat loss etc. For this study finite element analysis software COMSOL Multiphysics^{TM} is used.

2. MODEL DESCRIPTION

Fig. 1 shows the schematic illustration of the computational domain considered. Since, the physical geometry undertaken is symmetric, a three-dimensional symmetric computational domain is considered. The steel plate is 100 mm (length) x 40 mm (width) x 12 mm (height). The process parameters and material properties are given in Tables 1 and 2 respectively. Heat flux is considered on the top surface, bottom surface is insulated and convective and radiative losses are accounted for the rest of the surfaces including the weld pool region. The base metal is initially at ambient temperature. Gaussian distribution is used to simulate the arc heat flux.

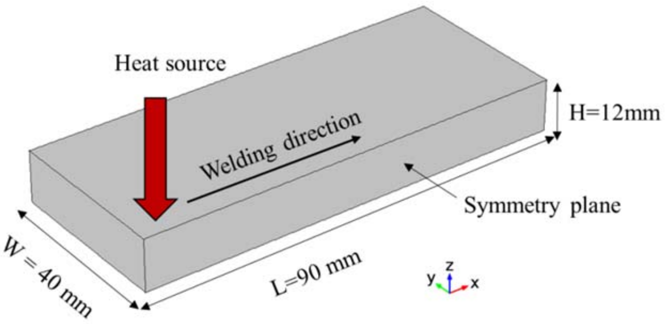

Fig. 1: Schematic view of symmetric computational geometry with dimensions.

Table 1: Process parameters used

Ambient temperature (K)	298
Voltage (V)	350
Current (A)	25
Arc efficiency (%)	75
Arc velocity (m s-1)	0.005

Table 2: Material property of mild steel

Melting point (K)	1723
Density (kg m-3)	7870
Emissivity	0.9
Convection coefficient (W m-2 K-1)	15

Table 3: Temperature dependent property of mild steel. [5]

Temperature (K)	Thermal Conductivity (W m-1 K-1)	Specific heat (J kg-1 K-1)	Enthalpy (J m-3)
273	51.9	450	1×10-9
373	51.1	499.9	2×10-9
573	46.1	565.5	2.65×10-9
623	41.05	630.5	3.8×10-9
823	37.5	705.5	4.1×10-9
873	35.6	773.3	4.55×10-9
993	30.64	1080.4	5×10-9
1023	26	931	5.23×10-9
1723	29.45	437.93	9×10-9
1783	29.7	400	1.1×10-10
1853	29.7	735.25	1.1×10-10
5273	42.2	400	1.25×10-10

3. EQUATIONS

3.1 Governing Equations

In the thermal analysis, the transient temperature field T of the welded part is a function of time t and the spatial coordinates (x, y, z), and is determined by the non-linear heat transfer equation as follows

$$\rho C_p \frac{\partial T}{\partial t} + q_o = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$

where Cp is specific heat of the material and q_o refers to rate of heat generation per unit volume.

One can define X=x-vt with x being the direction of the weld. In the coordinate system (x, y, z,t)

$$\rho C_p \left[\frac{\partial T}{\partial t} - v\frac{\partial T}{\partial X}\right] + q_o = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$

where v refers to electrode velocity along x direction.

3.2 Boundary conditions

During the welding process, heat is dissipated into the environment through convection and radiation heat losses from all the surfaces of the welded plate. Hence, in the current model it is assumed that heat is lost from top and lateral surfaces through radiation and convection.

The heat source energy can be approximated by a Gaussian distribution and the heat flux (q) on the top surface is given by the following expression

$$q = \frac{2P}{\pi W_o^2} e^{(-2r^2/W_o^2)}$$

where P is the arc power of heat source, W_0 is the radial distance in which energy density equals to e^{-2} times that at the centre of the heat source spot and r is the radial distance in meter.

Energy balance at the top surfaces leads to the following boundary equation

$$k\frac{\partial T}{\partial n} = q - h_c(T - T_\infty) - \varepsilon\sigma(T^4 - T_\infty^4)$$

where h_c is the convective heat transfer coefficient, ε is the emissivity, σ is the Stefan-Boltzmann constant and T_∞ is the ambient temperature.

In (13), terms on the right-hand side are heat energy from the heat source, convective heat loss and radiation heat loss to the surrounding, respectively.

Energy balance at the side surfaces leads to the following boundary equation

$$k\frac{\partial T}{\partial n} = -h_c(T - T_\infty) - \varepsilon\sigma(T^4 - T_\infty^4)$$

3.3 Initial conditions

The initial temperature (T_0) in the base metal is taken as equal to the ambient temperature (T_∞), i.e., 298 K.

4. RESULTS AND DISCUSSIONS

Fig. 2 shows the temperature distribution plots and layer and variation of the melt pool boundary in the welded plate at various times: t = 4 s, t = 8 s, and t = 12 s. Heat source is applied for 20 s since the arc velocity is 5 mm/s. The maximum temperature rises up to 2470 K which is higher than the melting point of steel which is about 1723 K. In this simulation, physical phenomena, as stated above, were considered. Fig. 3 shows plot of temperature versus distance along x-axis along mid plane surface at various times: $t = 4$ s, $t = 8$ s, and $t = 12$ s. It can clearly be seen that temperature varies exponentially with respect to distance.

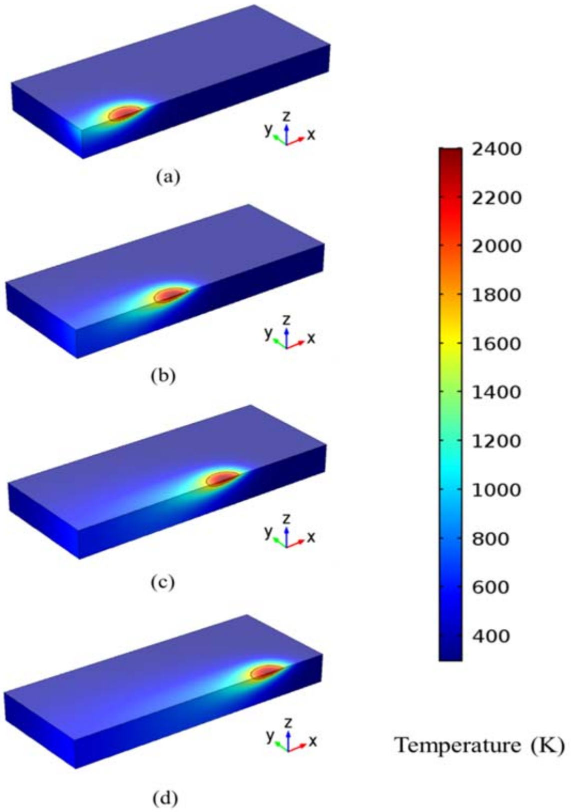

Fig. 2: Temperature distribution and weld pool boundary for various time instants (a) *t* = 4 s, (b) *t* = 8 s, (c) *t* = 12 s, and (d) *t* = 16 s.

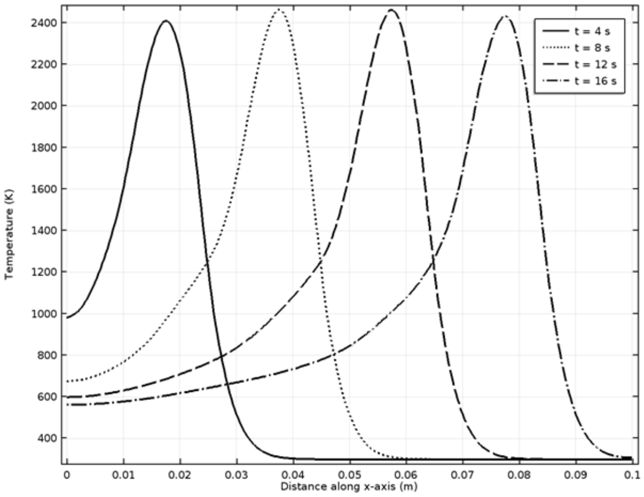

Fig. 3: Plot of temperature versus distance along x-axis along mid plane surface at various times t = 4 s, t = 8 s, and t = 12 s

5. CONCLUSION

In this study, modeling and simulation of semi-automatic arc welding process to join mild steel plates in butt joint configuration. The model considers temperature dependent material property, melting, solidification and phase change. The current model predicts temperature distribution in the welding. Weld pool boundary is also obtained from this model.

- Maximum temperature range near about 2500K.
- Temperature varied abruptly from the heat source point to away of heat source point, this is the one of the main reason of wide heat affected zone.
- It can be revealed from Fig. 3, that the shape of rare part of weld pool shape is more elongated that front part as during solidification of the weld pool, latent heat released from the weld pool which helps to melt the rear portion of it, and therefore the rare part more elongated.

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