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The Effect of Welding Process Parameter on Temperature and Residual Stress in Butt-Joint Weld of Robotic Gas Metal Arc Welding

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Abstract: In this paper, robotic gas metal arc welding (GMAW) of welded low carbon steel plate using butt-joint was studied. The distribution of the residual stresses in weld joint of optimization and non-optimum welding parameter such as welding current and speed was investigated by finite element method using ANSYS software. This analysis includes a finite element model for the thermal and mechanical welding simulation. The welding simulation was considered as a sequential coupled thermo-mechanical analysis and the element birth and death technique was employed for the simulation of filler metal deposition. The residual stress distribution and magnitude in the axial direction was obtained. The results shown that the optimum welding parameter able to lower the temperature and residual stress of the weld center area compare to non-optimum parameters around 8 percent for temperature and 1.5 percent for residual stress.

Key words: welding, butt-joint, gas metal arc welding, residual stresses, stress analysis, finite element method.

INTRODUCTION

Welding is widely used in automotive industries to assemble various products, also used in construction, ship building, steel bridges and pressure vessels (Stamenković and Vasović, 2009). The advantages of welding is as a joining process, include high joint efficiency, simple set up, flexibility and low fabrication costs . However when structures are manufactured by welding, a non-uniform temperature distribution is produced. This distribution initially causes a rapid thermal expansion followed by a thermal contraction in the weld and surrounding areas, thus generating inhomogeneous plastic deformation and residual stresses in the weldment when it is cooled (Armentani *et al*., 2007).

As it is well known welding process parameters like electrode diameter, electrode travel speed, thickness of the work piece, current and voltage greatly affect the temperature distribution patterns and hence residual stresses and distortions. Thus, it is important to evaluate the residual stresses due to welding. However evaluating residual stresses associated to a welded joint is extremely complicated. Difficulty in determining these stresses is emphasized by the thermal transient, by the variation of the thermal and mechanical properties of the material with the temperature and by the non linear heat losses (Armentani *et al*., 2007).

A large number of techniques have been used to predict temperature distributions, residual stresses and distortions in the welded joint such as stress relaxation techniques, diffraction techniques, cracking techniques and techniques. These techniques cannot obtain complete stress distribution and most of them are costly and time consuming and some of them are destructive. In recent years, numerical analyses are established to solve the complex engineering problems and among them evaluation weld-induced residual stresses.

In this paper, the finite element analysis is used to perform welding simulation and to predict weld-induced residual stresses in butt welding for two difference welding parameter. One of plates used optimum parameter and another one used non-optimum parameter. A moving heat source model based on Goldak’s double-ellipsoid heat flux distributions is applied in this study. A parametric model is adopted and the elements “birth and death” are used in single-pass butt welded joint in order to simulate the weld filler variation with time (Armentani *et al*., 2007, Goldak *et al*., 1984). The effect of thermal properties and weld efficiency on transient temperatures during welding was studied and the residual stresses after welding were determined by the finite element method. A fully coupled thermal–mechanical two-dimensional analysis was performed with the commercial software program ANSYS and heat flow was evaluated by a non-linear transient analysis.

Moving Distributed Heat Source:
Goldak’s Double-Ellipsoid Model:

In this study, the welded plates and filler material is considered as a solid body. A moving heat source model is developed to present the heat generated by the torch in the Robotic MIG welding process. The

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Goldak's double-ellipsoid heat source model is adopted to calculate volumetric heat flux distributions as heat input around the welding pool (Goldak *et al*., 1984). The heat source distribution is shown in Fig. 1

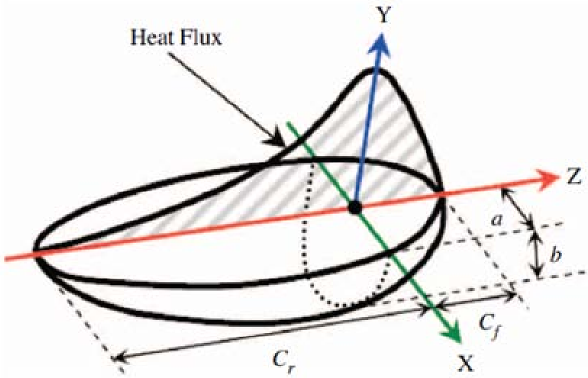


Fig. 1: Double ellipsoid heat source configurations.

It's combine with two different ellipses where one in the front quadrant of the heat source and the other in the rear quadrant. The power densities of the double-ellipsoid heat source, $q_f\ (x, y, z)$ and $q_r\ (x, y, z)$, describing heat flux distributions inside the front and rear quadrant of the heat source can be expressed as (Goldak *et al*., 1984):

Distribution inside the front quadrant, $q_f(\ watt/m^3\ )$

$$q_f(x,y,z) = \frac{6\sqrt{3}\, f_f Q}{abc_f\sqrt{\pi}} \, .\, e^{-3\frac{x^2}{a^2}} .\ e^{-3\frac{y^2}{b^2}} .\ e^{-3\frac{z^2}{c_f^2}} \tag{1}$$

Distribution inside the rear quadrant, $q_r\ \ (\ watt/m^3\ )$

$$q_r(x,y,z) = \frac{6\sqrt{3}\, f_r Q}{abc_r\sqrt{\pi}} \, .\, e^{-3\frac{x^2}{a^2}} .\ e^{-3\frac{y^2}{b^2}} .\ e^{-3\frac{z^2}{c_r^2}} \tag{2}$$

Where $Q = \eta\ IV$ is the energy input rate which is determined by efficiency η, welding current *I* and voltage *V*. respectively f_f and f_r are the fractional factors of the heat deposited in the front and rear quadrant, which can be determined by $f_f + f_r = 2$. The constants a, b, c_f *and* c_r as shown in Equation 1 and 2 are heat source parameters that define the size and shape of the ellipses therefore the heat source distribution (Goldak *et al*., 1984). The accuracy of the heat source definition is essential in the prediction of the two most important zones, fusion zone (FZ) and heat affected zone (HAZ), the peak temperatures and temperature distributions in the welding plate. Equation (1) and (2) of the Goldak's heat source model is defined as a function of position and time together with a number of parameters, which affect the heat flux magnitude and distribution.

Some experimental work has been carried out to investigate the relationships between the heat source definition and the weld pool shapes (Wahab and Painter, 1997). It has shown that welding process parameters, such as welding current and speed, have a great influence on the length of weld pool. Numerical values for different parameters in double ellipsoidal power density distribution equation are shown in Table 1.

Table 1: Numerical values for heat source parameters (Abid *et al*., 2005).

Parameter	Notation	Value	Value
Length of front ellipsoidal	c_f (mm)	10.1 mm	10.3 mm
Length of rear ellipsoidal	c_r (mm)	12.4 mm	12.9 mm
Depth of the heat source	a (mm)	6 mm	6 mm
Half width of the heat source	b (mm)	5 mm	5 mm
Front heat fraction	f_f	0.4	0.4
Rear heat fraction	f_r	1.6	1.6
Energy input rate	Q(W)	4752	5148
Heat Input per unit length	Q_1(J/mm)	712.4	618

MATERIALS AND METHODS

Calculation of Heat Flux Distributions for FE Models:

In order to simulate the welding torch movement with the specified speed, the calculated volumetric heat flux densities have to be assigned to specific elements around the welding area in the finite element model. The application of volumetric heat flux can be is achieved by implementing a user subroutine DFLUX, developed by the author in FORTRAN language (Abid and Qarni, 2009). With the programme the characteristics of the heat source, transient heat fluxes representing the moving distributed heat source can be calculated on specific positions in the welding area.This provides an effective tool to modeling effects and sensitivities of welding process parameters and characteristics of the heat source model on temperature of the weld plates.

Thermal Simulation of Plate Butt Joint Welding:

Geometry Model:

The welding process of butt-weld joint of low carbon steel was simulated and the size of plate is 200mm x 120mm and the thickness of the plate is 6 mm. Since the weld sample taken for investigation was symmetrical, the symmetry axis was at the weld centre. Half of the weld section was taken for investigation. The model coordinate system and mesh divisions are shown in Figure 2 and Figure 3. The *x*, *y* and *z* directions represent the width, thickness and length of the model, respectively.

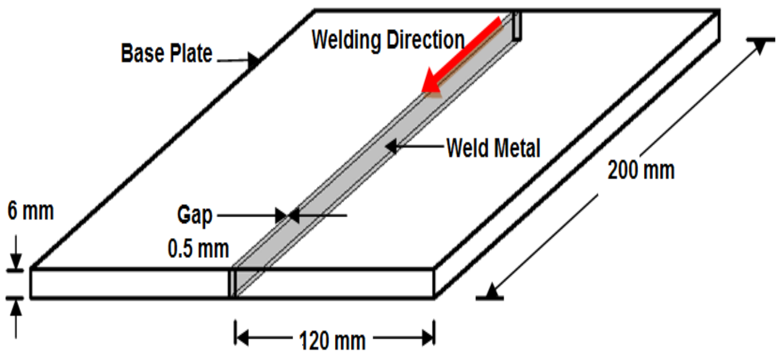


Fig. 2: Geometry of model.

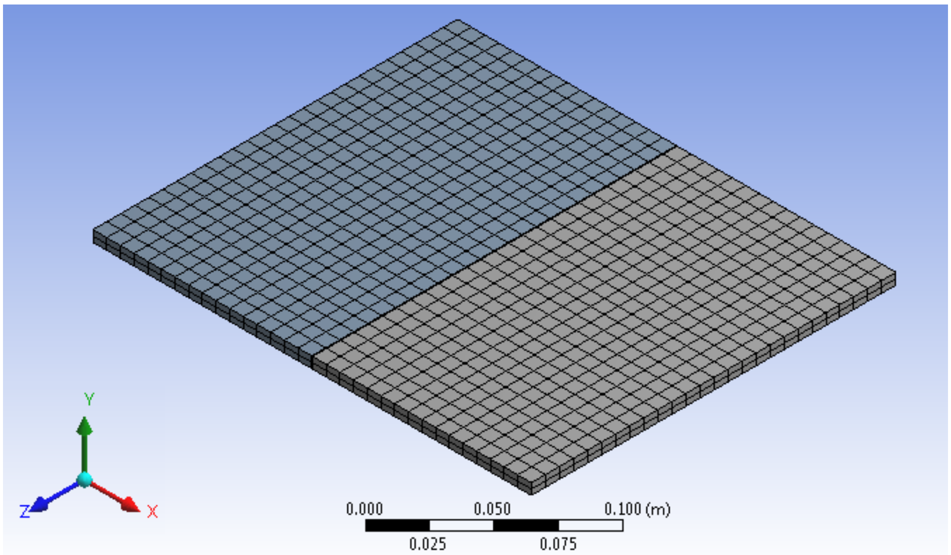


Fig. 3: Meshing of model.

The three-dimensional mesh consisted of 1824 elements and 11055 nodes as shown in Figure 3. The size of the elements, used at the root of the welded joint is 7.7 x 3 x 9.4 mm in size and constant size to all models. The same size mesh is used for both the thermal and mechanical analysis and the numbers were consistent for all models.

Welding Parameters and Material Model:

Two type of welding process parameter are used as a model in this study. One of them is optimum parameter which has a good relationship between welding process parameter and mechanical function and another one is the non-optimum welding parameter as shown in Table 2.

Table 2: Welding Parameters.

Parameter	Units	Optimum Value	Non-optimum value
Welding voltage	V (V)	24	26
Welding current	I (A)	220	220
Arc efficiency	η	90	90
Welding speed	V_w (mm/s)	6.67	8.33

The material of the plate is low carbon steel and the thermal conductivity, specific heat and density at room temperature are defined to be k = 41 W m^{-1} °C^{-1}, cp = 434 J kg^{-1} °C^{-1} and ρ = 8131 kg/m^3, respectively [7]. The dependences of thermal conductivity and specific heat on temperature are considered as shown in Table 3. Therefore, the material properties at elevated temperatures can be calculated by multiplying factor values with the material property values at the room temperature. The melting temperature of the material is defined as 1440 ◦C and the temperature for the phase transformation is 723 ◦C.

Table 3: Material properties (Stamenković and Vasović, 2009).

Temperature (°C)	Specific Heat (J/kg°C)	Thermal Conductivity (W/m °C)	Density (kgm^{-3})	Yield Stress (MPa)	Thermal Expansion Coefficient (10^{-5} / °C)	Young Modulus (GPa)	Poisson's Ratio
0	400	60	7880	250	1.15	210	0.3
100	500	50	7880	240	1.20	200	0.3
200	520	45	7800	230	1.42	200	0.3
400	650	38	7760	200	1.45	170	0.3
600	750	30	7600	180	1.45	80	0.3
800	1000	25	7520	150	1.45	35	0.3
1000	1200	26	7390	125	1.45	20	0.3
1200	1400	28	7300	80	1.45	15	0.3
1400	1600	37	7250	35	1.45	10	0.3
1550	1700	37	7180	30	1.45	10	0.3

Thermal Model:

In the thermal analysis, the transient temperature field T of the welded plate is a function of time t and the spatial coordinates (x, y, z), and is determined by the non-linear heat transfer equation (Incropera and DeWitt, 1996):

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q_{int}=\rho c_{\mathrm{p}}\frac{\partial T}{\partial T} \quad (3)$$

where Q int is the internal heat source rate, k, cp and ρ are the conductivity, specific heat and density of the plate material, respectively. These material properties are defined in Section 3.2. As discussed in Section 2.1, to determine the heat source of a butt joint welding, the energy input rate Q and welding speed for optimum welding parameter defined as 4752W and 6.67 mm/second and for non-optimum welding parameter is 5148 W and 8.33 mm/second respectively.

Calculation of the distribution and magnitude of heat fluxes, the heat source parameters are determined through an approximate relationship between the weld pool length and energy input suggested by Wahab and Painter (1997) and of Godlak *et al*. (1984). In order to investigate the effect of welding process parameters on the residual stress distribution and variation, the energy input rate is increase from 4752 W to 5148 W. The welding speed is increased from 6.67 mm/second to 8.33 mm/second. The values of a, b, c_r and c_f are changed as shown in Table 1. Thus, the change of heat source parameters results in the changes of the heat flux distribution and the peak heat flux values in the front and rear quadrants of the double-ellipsoid heat source.

Analysis Set-Ups:

The ambient temperature is set to 30° C. Welding process begins at the start-node of the weld-line. On the optimum welding parameter model the heat source starts to move along the trajectory at the speed of 6.67 mm/s in the z-direction and reaches the end-node at 200 mm of the weld-line after 30 s. Another model which has non-optimum welding parameter the heat source starts to move along the trajectory at the speed of 8.33 mm/s in the z-direction and reaches the end-node at 200 mm of the weld-line after 24 s.

It is a great challenge to consider all factors at the same time; so generally the models include some approximations so that this work deals with the following main assumptions and features about the thermal model:

1. The displacements of the parts, during the welding, do not affect the thermal distribution of the parts themselves.
2. All the material properties are described till to the liquid phase of metal.
3. Convection and radiation effects are considered.
4. The element birth and death procedure is used.

RESULTS AND DISCUSSIONS

Temperature Distribution:

Thermal simulation results in Figure 4 shown the temperature distribution of the welded plate on the weld center line at the coordinate of z = 100 mm versus the direction of x axis, starting with x = 0 after 15 second from the starting point. As can be seen from the figure, the temperature at this point for optimum welding parameter reaches maximum value of 973.63 ° C at the time of 15 second and for non-optimum welding parameter reaches 1057.7 ° C in the same time. For better illustration the distribution of weld pool in fusion zone is represented by its surfaces with temperatures of 973.63 ° C for optimum parameter and 1057.7° C for non-optimum parameter as shown on in Figure 4 and Figure 5. It is shown that the optimum parameters are able to lower the temperature at the weld area.

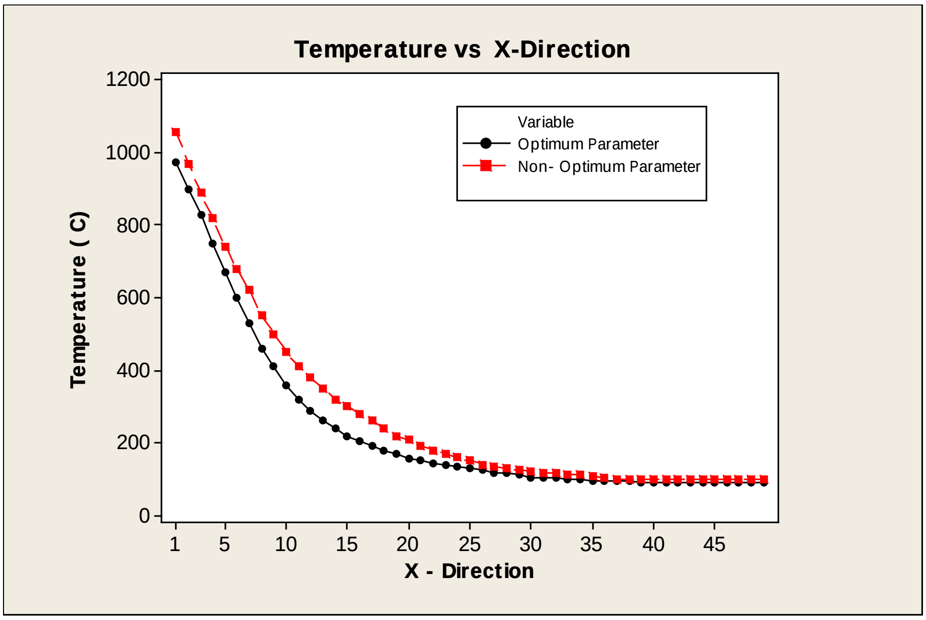
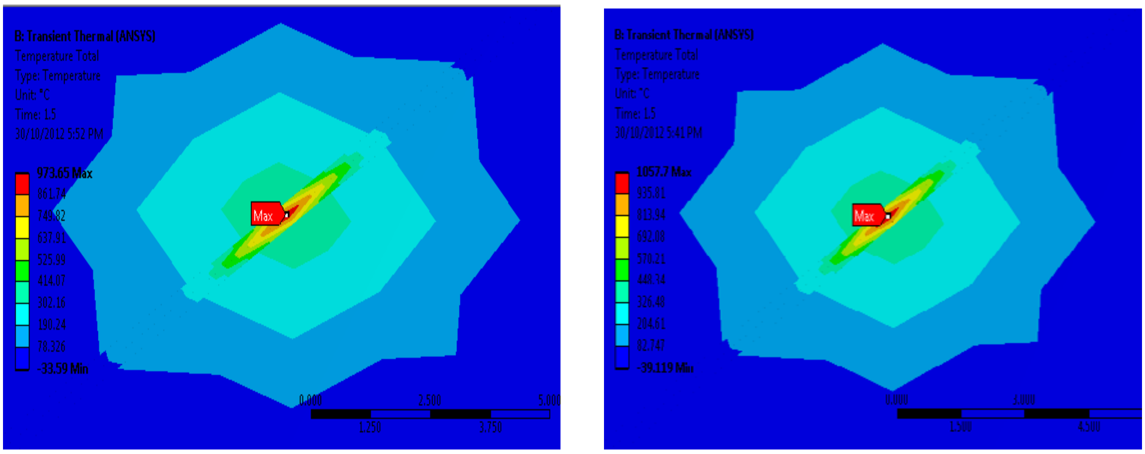


Fig. 4: Graph Comparison of temperature profile in the middle of the plate, *z* = 100 mm.

Residual Stress Distribution:

Residual stresses are evaluated using the same mesh that was used for calculating the temperatures. Normal stresses parallel to the direction of the weld are called longitudinal residual stresses and stresses along the direction of axis x are called transversal residual stresses. The variations of transversal residual stresses versus direction of x in the middle of the plate at the coordinate of *z* = 100 mm are shown in Figure 6. The simulation results reveal that the non- optimum welding process parameter will increase the residual stresses in the butt-joint welding compare with optimum welding process parameter. As can be seen from the Figure 6, the residual stress of optimum welding parameter reaches a value of 266 MPa and increase to value of 270 MPa for non-optimum welding parameter. Its shows that the tensile residual stresses for the both welding parameter are higher in regions near the welding line, then decrease close to zero as the distance from the welding line increases. The comparisons of longitudinal residual stresses in the *z* direction along the weld in the plate at mid span also show that the non-optimum welding parameters will be increase the residual stress compare with optimum welding parameters as shown Figure 7.



(a) Optimum parameter (b) Non-optimum parameter

Fig. 5: Temperature fields of welded plates in the middle of the *z* direction.

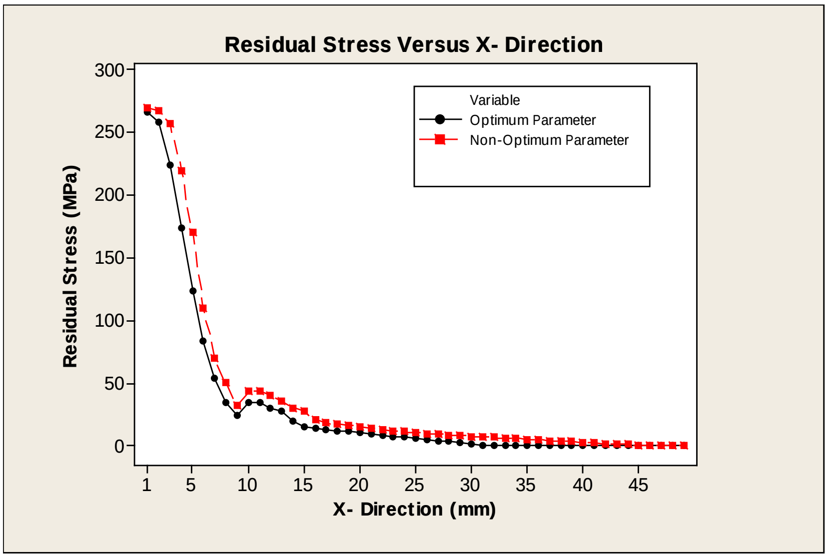


Fig. 6: Graph Residual Stress in *x* direction in the middle of the plate, z = 100 mm.

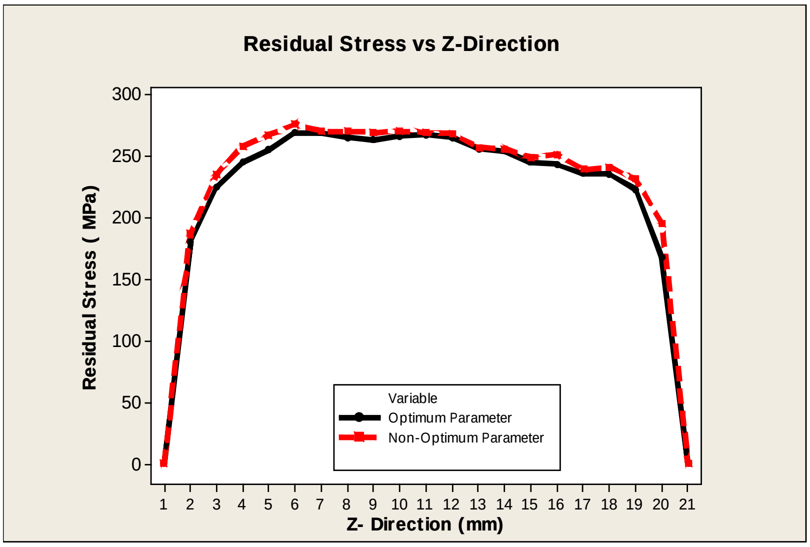


Fig. 7: Graph Residual Stress in *z* direction in the plate at mid span along the weld.

Conclusions:

The distribution of the residual stress in the weld zone of low carbon steel using Robotic Gas Metal Arc Welding (GMAW) was determined using ANSYS finite element software. It is seen that the residual stress are increasing in non-optimum welding parameter compare with optimum welding parameter. The simulation results reveal that there is a stress gradient around the fusion zone (weld center). The residual stress on the weld surface is 200–300 MPa in z- direction. This gradient is high near the fusion zone and then decrease close to zero as the distance from the welding line increases. The results shown that the optimum welding parameter able to lower the temperature and residual stress of the weld center area compare to non-optimum parameters around 8 percent for temperature and 1.5 percent for residual stress.

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