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Analytical and Numerical Simulation of Temperature Field and Residual Stresses of Butt Weld in Steel Plates used in Ship Manufacturing

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Abstract: A calculating process for analyzing temperature field and residual stresses in the butt weld in steel plates used for ship manufacturing has been presented. Present study is based on software ANSYS 9.0 and includes 3-dimensional uncoupled heat-mechanical model and analytical field stress 2-dimensional model using programming software MATLAB 7.1 and the method of advanced elastic. The model of finite element was used in order to evaluate temporary stresses and residual stresses of the weld. At first, 3-dimensional model is developed in order to study temperature field and residual stresses. Then 2-dimensional model was used in order to study temperature cycle and welding residual stresses. Using the 2-dimensional model can save in much time of calculation. In this research testing results of reference were used to show accuracy of models. The results of both 2 and 3-dimensional models are very good considering the test model.

Key words: Finite element model, numerical simulation, advanced elastic method, residual stresses

INTRODUCTION

Welding is an assured and effective method of metal joining that is approximately used in all industries. Butt weld is a common type of welding to join steel plates. Considering large thicknesses of plates, butt weld in most of the cases consists of various procedures. The area close to welding line includes a separate heat cycle. Heat cycle causes heat or cool non-monotonously in materials, which causes to create deformation and as a result creation of residual stresses in the welded section. Attendance of residual stresses lowers efficiency of welding part. Elastic residual stresses are usually destructive and they raise the risk of fatigue, crack due to erosion and failure (Murugan *et al*., 2001). Therefore we need a proper estimation of welding.

Distribution of residual stresses in weld depends on various factors, dimensions of the structure, properties of materials, block conditions, input heat, welding pass and welding sequence. Thus for multi-pass welding, residual stresses may be so complex that estimation of its distribution will not be available (Deng and Murakawa, 2006). In the last decade many models of finite element have been presented by Goldak *et al*. (1984), Mochizuki *et al*. (2000), Deng *et al*. (2006) and Jiang *et al*. (2005) that all of them are for forecasting temperature field and residual stresses of butt weld in steel plates.

Some of the most important relations to estimate of residual stresses are referred and finally stresses resulting from analytical are compared to numerical equations and also with the presented formulas by some of the researches.

Considering Masubuchi and Martin (1966) relations, distribution of longitudinal-stresses σ_x can be estimated in the form of Eq. 1:

$$\sigma_{res} = \sigma_m \left(1 - \left(\frac{y}{b}\right)^2\right) \exp\left(-0.5\left(\frac{y}{b}\right)^2\right) \tag{1}$$

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Tada and Paris (1983) has suggested the following equation for longitudinal residual stresses:

$$\sigma_{res} = \sigma_m \frac{\left(1-\left(y/b\right)^2\right)}{\left(1+\left(y/b\right)^4\right)} \quad (2)$$

where, σ_m is the maximum stress occurring in the weld metal, y is co-ordinate in the transverse direction and b is the half width of the tension zone of longitudinal residual stresses.

Brickstad and Josefson (1998) applied a different 2-dimensional model in order to numerically simulate a three-pass butt weld on a 40 mm plate with non-linear heat-mechanical finite element. Wen *et al*. (2001) used 2-dimensional model of finite element and obtained three-pass welding on a 19 mm plate.

Li *et al*. (1995) developed a full 3-dimensional model with little gap which requires many to determine its accuracy.

Three-dimensional model can distribute heat and residual stresses in welding procedure; however, achieving this goal is time consuming. The reason for this matter is that the welding phenomenon is a non-linear transitory problem. If we use 2-dimensional instead of 3-dimensional, obviously there will be much saving in time. In the present research whose principles is based on ANSYS Software, at first it was tried that a 3-dimensional model to be presented to simulate distribution of heat and also residual stresses in welding and then 2-dimensional model was presented to calculate heat and residual stresses and finally the results were compared with the results of test and analytical formulas in order to study accuracy of the research.

THREE-DIMENSIONAL MODEL OF FINITE ELEMENT

The used materials are selected from low-carbon steel with a length of 600 mm and the width of 300 mm and thickness of 25 mm. The specimen edge has been shown in Fig. 1 (Lee *et al*., 2004). Welding is started in the direction of x and on the point at the beginning and it is stopped at the end of the plate. The type of filling material is the same as the base metal. The procedure is also electrical arc welding. Welding procedure includes one-pass welding. Maximum temperature of the pool is 1600°C that conforms to practical procedure of welding. When the torch moves far from the edges, the temperature field will take a stable status.

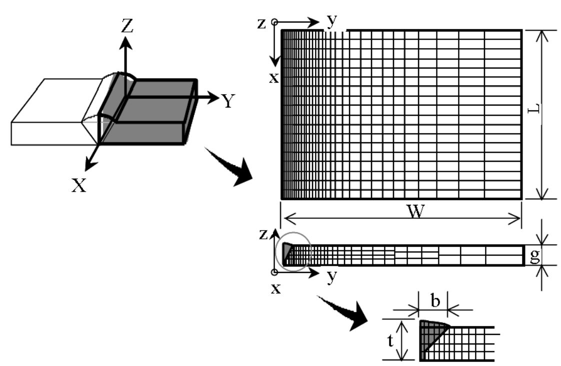

Fig. 1: Finite element models of a butt-welded plate (Lee *et al*., 2004)

Table 1: Physical properties for low carbon steel according ABS rules

T	20	93	204	316	427	538	649	760	871	982	1093	1204	1316	1427
k	59.95	62.52	63.7	62.9	61.922	58.36	60.07	44.64	45.78	47	45.66	49.047	49.97	50.87
ρ	7861	7833	7806	7750	7722.7	7667	7640	7612	7612	7612	7612	7612	7612	7612
σ_y	248	221	200	173	152	117	98	41	21	6.9	5.52	4.83	0.69	0
E	207	204	199	191	179	157	97	35	29	20.7	14.49	8.28	2.07	0
E_t	11	10.9	10.6	10.2	9.6	8.35	5.2	1.9	1.6	1.1	0.759	0.414	0.069	0
v	0.3	0.31	0.32	0.34	0.3	0.37	0.4	0.4	0.4	0.42	0.423	0.447	0.465	0.46

T (°C): Temperature based on centigrade degree, k (W/m.°C): Coefficient of heat conduction, ρ (kg m^{-3}): Density, σ_y (MPa): Yield stress, E (MPa $\times 10^3$): Young module, E_t (MPa $\times 10^3$): Tangent module, v: Poisson ratio

Here temperature distribution and also the evolutionary course of residual stresses have been presented by the aid of finite element tools. In order to simulate mechanical heat behavior of welding area non-coupling formulas have been used. Due to the reason that change in dimensions of welding is very little, the energy of performed mechanical operations is not considered in comparison with heat energy of welding arc.

The problem of conducting heat is solved independently of stress problem in order to obtain the record of temperature. Also in formulating, the role of transitory temperature in the analysis of stress has been executed with the actions of physical and mechanical properties depending on temperature. The solution process consists of two stages, at first distribution of temperature and the history of welding are obtained by analysis of conducting heat. Then temperature history is considered as load in mechanical elasto-plastic calculation. In this research all of these phases are performed by the ANSYS code. The temperature physical and mechanical properties of base metal have been given in Table 1.

Heat Analysis

Three dimensional models of finite element with 900 full 8-spot elements 2020 spots have been indicated in Fig. 1. Due to its symmetry, only half of the model has been considered for the analysis. In the welding area, the micro-elements have been regarded. The smallest size of elements is $1.5\times1.5\times5.3$ mm^3. To model the movable source, the method of death and birth of elements has been used. In this manner that at first all the elements of filling metal are put in the state of death and in each stage several of them are alive and they are put under maximum temperature. This is the way, the stages are performed in order to finish the work. Then it is possible to read the temperature of each point in various phases and draw the temperature based on the time period. While welding, the dominant equation is given as follows for transferring transient temperature:

$$\rho c \frac{\partial T}{\partial t}(x,y,z,t) = -\nabla \cdot \vec{q}(x,y,z,t) + Q(x,y,z,t) \tag{3}$$

where, ρ is density of the substance and c is capacity of special temperature and T is existing temperature and $\vec{q}$ is vector of heat flow and Q is the rate of produced heat and x, y and z are the coordinates in reference system and t is time, ∇ is operator of space gradient.

Isotropic heat flow is expressed as follows:

$$\vec{q} = -k\nabla T \tag{4}$$

where, k is coefficient of conduction depending of the temperature. Q in Eq. 3, (the power of welding heat source) is obtained using the current of 250 Amp and voltage of 30 v and also coefficient of arc output 70% (for welding MIG) equal to 5250 ($Q = \eta VI$). The reason for using this current and voltage is only for its common application and also comparison with reference (Brik-Sørensen, 1999). Waste of energy is considered in the form of radiation in the spots with high temperature close to welding area and loss is in the form of transfer in low temperatures and far from the welding area.

Coefficient of transferring heat depending on time is considered as follows (Brickstad and Josefson, 1998):

$$h=\begin{cases} 0.68T\times10^{-8} \quad \left(W/mm^2\right) & 0<T<500°C \\ \left(0.231T\text{-}82.1\right)\times10^{-6} \quad \left(W/mm^2\right) & T>500°C \end{cases} \tag{5}$$

where, T is temperature. In order to calculate heat transfer in welding pool, a hypothetical heat transfer coefficient that is many times greater than its amount in room temperature is considered for the temperature higher than melting temperature. Heat effect as a result of hardening welding pool in the amount of covert melting temperature has been considered.

Mechanical Analysis

The model which we applied in heat analysis is used here as well, of course except the type of element and boundary conditions. In mechanical analysis temperature procedure is used which is obtained in the sage of heat analysis. During welding process, since transfer of solid-state phase does not occur in low-carbon steels, total rate of strain is dividable to three parts:

$$\dot{\varepsilon} = \dot{\varepsilon}^{e} + \dot{\varepsilon}^{p} + \dot{\varepsilon}^{th} \tag{6}$$

The right elements of Eq. 6 include elastic, plastic and heat strains. Elastic strain is modeled using Hook Isotropic Law with Young Model and Poisson's Ratio dependent on temperature in accordance with Table 1. Heat strain is calculated using dilation coefficient dependent on temperature. For plastic strain of the model with yield level of Von Mises, mechanical properties dependent on temperature and hardening linear cinematic model has been obtained. Cinematic hardening has more importance compared to the other hardenings because in materials welding the materials are only under loading and taking load (Radaj, 2003).

ANALYTICAL MODEL OF HEAT FIELD AND RESIDUAL STRESSES

In this section advanced elastic method has been used for calculating transitory strains, transitory stresses and residual stresses in one dimension. This process has been presented by Mendelson and it was applied for solving welding problem the first time by Tall and later by Masubuchi (Vitooraporn, 1990). In order to analyze the stresses in middle of cutting profile of the plates, a band element perpendicular to welding line such as what is shown in Fig. 2 shall be considered.

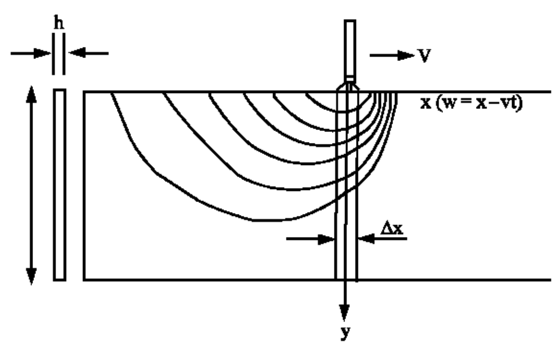

Fig. 2: Strip element for one dimensional analysis

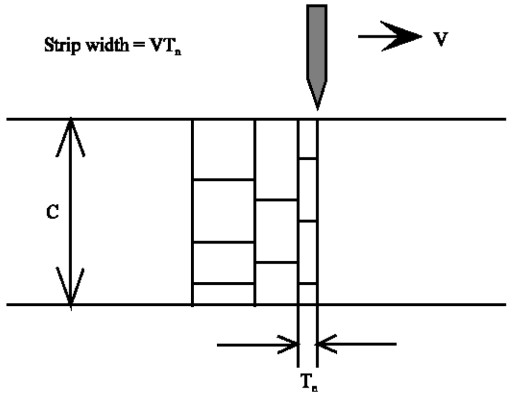

Fig. 3: Temperature distribution in analytical one dimensional model

The two edges of the band are straight in x and x + Δx. This is the same hypothesis applied in the theory of simple beam.

One main hypothesis applied is in its one-dimensional analysis that is $\sigma_y = \tau_{xy} = 0$. Equilibrium equation in the direction of x without presence of each type of foreign force becomes as follows:

$$\frac{\partial \sigma_x}{\partial x} = 0 \tag{7}$$

This means that σ_x has no change in the direction of welding. In case the temperature is changed in this direction, will the stress also change as well. Thus equilibrium conditions are not satisfied by the model. In order to remove this problem, we can suppose that in on particular time of t each film has a specified temperature.

Now with this supposition we can have various films in the direction of welding with various temperatures (Fig. 3). During each time period, temperature is considered fixed in the direction of width. With new time period, temperature changes and we will have a new distribution of the stresses. The width of each film is obtained from multiplying time period by speed. The stress in each period can be obtained from advanced elastic method. Then the relation of stress-strain is used and the obtained strain will satisfy adaptation equations for 1-dimensional analysis.

$$\frac{\partial^2 \varepsilon_x}{\partial y^2} = 0 \quad \Rightarrow \quad \varepsilon_x = C_1 + C_2 y \tag{8}$$

For one film the strains will be in the form of relation (9).

$$\varepsilon_x = \frac{\sigma_x}{E} + \alpha\Delta\theta + \varepsilon_x^{pl} \quad \Rightarrow \quad \sigma_x = E\left(\varepsilon_x - \alpha\Delta\theta - \varepsilon_x^{pl}\right) \tag{9}$$

$\varepsilon_x^{el} = \frac{\sigma_x}{E}$ is the elastic part of strain, ε_x^{pl} plastic part of strain and $\varepsilon_x^{th} = \alpha\Delta\theta$ are heat strains.

The equilibrium of forces and moments also shall be established for σ_x as well.

$$\begin{aligned} &\int_0^c \sigma_x \, dy = 0 \\ &\int_0^c \sigma_x \, y dy = 0 \end{aligned} \tag{10}$$

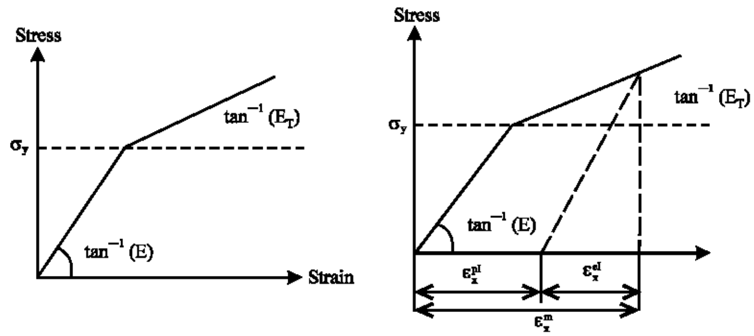

Fig. 4: Schematic of calculation plastic strain

C is the width of the plate. With replacing ε_x in σ_x and with using by two above equations we can obtain the fixed amounts of C_1 and C_2 and finally transitory strain is obtained as follows:

$$
\begin{aligned}
&\varepsilon_x = (A_1 - A_2 y)\int_0^c E(\alpha\Delta\theta + \varepsilon_x^{pl})dy - (A_2 - A_3 y)\int_0^c E(\alpha\Delta\theta + \varepsilon_x^{pl})ydy \\
&A_1 = [\int_0^c Ey^2\, dy]/B \\
&A_2 = [\int_0^c Ey\, dy]/B \\
&A_3 = [\int_0^c E\, dy]/B \\
&B = [\int_0^c E\, dy][\int_0^c Ey^2\, dy] - [\int_0^c Ey\, dy]^2
\end{aligned}
\tag{11}
$$

Equation 11 is not enough for solving the problem alone. A relation between stress and strain is required. In each time period (in each film) total strain is calculated in each film. It is supposed that in Eq. 9 plastic strain is zero $(\varepsilon_x^{pl}(y) = 0)$. Then mechanical strain is obtained in the following form:

$$\varepsilon^m = \varepsilon_x(y) - \varepsilon_x^{th}(y) = \varepsilon_x(y) - \alpha\Delta\theta(y) \tag{12}$$

With supposition from linear relation between stress and strain the first estimation will be obtained from plastic strain such as Fig. 4. This amount is again used in Eq. 11 in order to obtain the second estimation of the strain and this process will continue to obtain converging amount.

During the calculation of total strain in each time period, plastic strain is obtained from off-loading and loading of the previous stage. With calculating transitory strains, the calculation of transitory strains in plate is also made possible and residual stresses are obtained.

Computer programming has been presented to the language MATLAB. In the calculation of stresses various integrations are required. In the present program 21 integrated spots with various spans have been considered. In integrating the general figure of the Method of Newton-Kats has been used. This program consists of the properties depending on time and can solve each problem of butt weld on smooth plate with limited width. The output of each step includes total strain, mechanical strain, plastic strain and stress in each pre-determined point in each width distance from welding line. Temperature distribution can be entered separately or done calculated with similar program using linear heat source.

CONCLUSION

As it was mentioned, using heat analysis of finite element forecasting capability of heat in the first stage is created. Also in order to use analytical method for forecasting residual stress, temperature

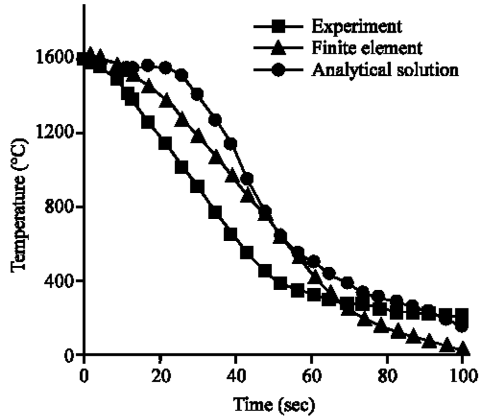

Fig. 5: Comparison of temperature fields with test results (Brik-Sørensen, 1999)

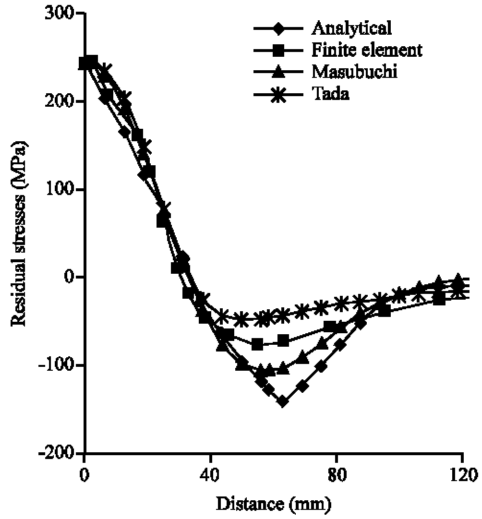

Fig. 6: Comparison of obtained stresses with the said methods

distribution required in this distribution analytical solution obtained from reference by this researcher has been used. Also we can use Rosenthal distribution. For more description (Rahmati, 2007). In Fig. 5 distribution of obtained temperature has been compared with temperature distribution resulted from reference test (Brik-Sørensen, 1999) in order to observe accuracy rate.

In comparison, the method of finite elements was compared with analytical 1-dimensional method and also relations of Masubuchi and Tada. These stresses are longitudinal stresses and they have been obtained for middle profile. Considering Fig. 6 it is clear that analytical relation of residual stress has higher minimum compared to other stresses and after that there is the relation of Masubuchi and then solution of finite element and after that there is Tada as well. Considering obtained amounts we can state that the applied finite element method is a proper method. We shall consider that working with this method is difficult and requires so much time. But instead we can use the average of relations (Eq. 1, 2). One should pay attention that for using these relations, the maximum stress and also half-width of tension stress are required. In Fig. 6 this comparison has been given for the middle profile of the sample. These results have been indicated in Table 2.

Table 2: Comparison of obtained stresses with said methods

Methods	Maximum stresses (MPa)	Maximum tension stresses	Distance of maximum pressure stresses from weld line (mm)	Half width of tension stresses (mm)
Analytic stresses	120.6	248.5	61	34.5
Finite element	80	248.5	55	32.5
Masubuchi	110	248.5	58	33.5
Tada	49	248.5	52	33.5

In this research 3-dimensional models of finite element and analytical model have been presented in order to enable us to forecast heat field and residual stresses in welding by their aid. In comparison with laboratory results we can conclude that computer model is an appropriate model for forecasting heat cycle and residual stresses.

Considering the results of simulation and the test results the following are conclude:

- Concerning the results of 3-dimensional model we can find that motion of heat source has a stable state and residual stresses also take a congenial state, of course, except the areas close to the beginning point.
- In the present research, both models of finite element and analytical forecast heat cycle and residual stresses with high precision. Using the model of finite element we can obtain many details about heat distribution and residual stress. Analytical model is not able to indicate as many details as finite element model, but it saves a lot of time.

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