The Effect of Heat Input Parameters on Residual Stress Distribution by Numerical Simulation

Mahmood Hasan Alhafadhi¹, Gyorgy Krallics¹
1Institute of Physical Metallurgy, Metal Forming, and Nanotechnology, University of Miskolc (Hungary)

E-mail: mahmoodhs199@gmail.com

Abstract. This paper deals with Numerical Simulation to analyze the behavior of residual stresses in the plate. The residual stresses at the surface of some weld specimen by using the finite element technique. The results of the numerical simulation analysis were compared with three cases data to evaluate the accuracy of Goldak model (double ellipsoidal heat distribution model). Based on this study, a modeling procedure with reasonable accuracy was investigated. The developed finite element modeling was used to investigate the effects of welding heat input on magnitude and distribution of welding residual stresses in a welded plate made of steel. The different directions of residual stresses in the surface of the plate of 25 mm thick for V-groove shape were studied. It is shown that the welding heat input parameters have a significant effect on the magnitude and distribution of residual stresses.

1. Introduction
Welding is reliable and efficient metal joining processes used in almost all industries. Arc welding is extensively used mainly for making plates. The finite element method applied to simulate the welding processes has focused mainly because of the increase in the capacity of computers and availability of commercial numerical simulation code. The numerical simulation has been the most common for analysis and simulates the welding problems which include thermal and mechanical with each other. When two part of plates are welded together residual stress is created in the vicinity of weld due to the arc welding of the plates. The elastic-plastic response of creating the residual stresses by thermal cycle can be responsible for many problems in weld such as cracking or failures in weld structures. [1-5].

Generally, tensile residual stresses are increasing weld fatigue damage, stress cracking and fracture. It has been observed in near the weld fusion on surfaces of plates for example. The distribution of residual stresses changes in different positions on welding, so residual stresses plays a very important role to measure weld quality. The first studies used numerical simulation of welding process were employed by Friedman (1975) who studied the thermal and mechanical FEM model to determine the temperature and stresses distribution. Finite Element simulation has become a common tool for the prediction of welding residual stresses. A substantial amount of simulation and experimental work and studies focusing on welding with emphasis on plates welding is available in the literature [6-13]. Morrow and Sinclair [14] studied the prediction of residual stress relaxation based on mean residual stress relaxation observed in the axial fatigue test. Dong (2003) [15] described thermal-mechanical analysis provides accurate results and simplifies the numerical solution. El-Ahmar (2007) [16] explained that the effect of finite elements with simulations is not significant in the welding process application. Ziolkowski and Brauer (2009) [17] used the combination of Gaussian distribution on the surface and along the thickness with 3D distribution, by applying the heat source model. Wu et al. (2009) [18] studied the Goldak model in double ellipsoid with spherical and cylindrical volumes through the thickness. The study aim to investigate the mechanism of residual stress with different
parameters Goldak model and analytical model for under various cases in 2D FE simulation of a single pass weld joint geometry is performed using Marc software.

2. Simulation model

Two plate halves 25 x 500 x 1000 mm are butt-welded together. A double V-groove is made in the plates. The plates are welded from the top using an arc welding process. No weld is made in the lower groove as shown in fig. 1 (a) is considered for the analysis. Due to symmetry conditions, only one of the plates is analyzed using the same conditions. The meshed model of the plate and the welding local coordinate system is also shown in fig. 1 (b).

Both the weld filler and base metal are assumed to be made of the same steel material. The initial temperature for the base metal is taken at 30°C.

Table 1. Welding parameters (Mechanical and Thermal properties)

| Mechanical Properties               |               |
|-------------------------------------|---------------|
| Young’s Modulus                     | 2.0x10^5 MPa  |
| Poisson’s Ratio                     | 0.35          |
| Mass Density                        | 7850 kg/m³    |
| Yield Stress                         | 3.0x10^2 MPa  |
| The coefficient of thermal expansion| 1.0x10^-5°C   |
| Thermal conductivity                | 40 W/m²°C     |
| Specific heat                        | 500 J/kg°C    |

The welding parameters mechanical and thermal properties shown in Table 1. Solid-Solid phase transformations in the steel during heating and cooling are not considered in the current study. The solid-liquid transition is accounted for by providing a latent heat of fusion of 250 kJ/kg with a solidus temperature of 1100°C and a liquidus temperature of 1200°C. Symmetry boundary conditions are applied at one end of the structure and applied at the other end. A volumetric weld flux is applied to all elements of the base metal. Based on the dimensions given for the welding flux, Marc automatically determines which base elements actually receive the flux. A convective film boundary condition is applied to all the exposed edges of the base metal. The heat transfer coefficient is taken as 12 W/m²°C and the ambient temperature is taken as 30°C.

Simulation process

An analysis is done with the plate is symmetrical, half of the plate is only modeled. By using mesh optimization technique fine mesh generated around and in weld zone and comparatively coarse mesh far from the weld line. The governing equation for transient heat transfer during welding is given by

\[ p_c \frac{\partial T}{\partial t}(x,y,z,t) = -\nabla q(x,y,z,t) + Q(x,y,z,t) \]  \hspace{1cm} (1)
Where \( p \) is the density of the materials, \( c \) is the specific heat capacity, \( q \) is the heat flux vector, \( T \) is the temperature, \( Q \) is the internal heat generation rate, \( x, y \) and \( z \) are the coordinates in the reference system, \( t \) is time and \( \nabla \) is the spatial gradient operator. To perform the analysis, the heat distribution model is modified in order to accommodate cylindrical coordinates. The plate geometry is generated, and welding torch is applied using different welding parameters given in Table 2. Fig. 2 shows the various weld parameters, in a double ellipsoidal distribution proposed by Goldak et al. [19].

![Figure 2. Weld parameters](image)

Table 2. FE model with different parameters

| Specimen | Forward length (mm) | Rear length (mm) | Width (mm) | Depth (mm) |
|----------|---------------------|-----------------|------------|------------|
| Case 1   | 5.5                 | 5.5             | 2.75       | 11         |
| Case 2   | 6                   | 6               | 3          | 12         |
| Case 3   | 7                   | 7               | 3.5        | 14         |

The parameters \( a, b, c_1 \) (forward length) and \( c_2 \) (Rear length) are related to the characteristics of the welding heat source. To compare and analyze the result the different parameter (Goldak model) as shown in Table 2. The heat from the moving source is applied as a double ellipsoidal distribution (Goldak model) is explained by the following equations:

\[
Q(x,y,z,t) = \frac{\eta V I}{abc\pi} \frac{1}{\sqrt{\pi}} e^{-\frac{3}{t}} \left( \frac{3v^2}{c^2} - 3\left(\frac{v}{b}\right)^2 - 3\left(\frac{v}{a}\right)^2 \right)
\]

Where \( x, y, \) and \( z \) are the local coordinates of the double ellipsoidal model. \( fi \) is the fraction of heat deposited in the weld region. \( V \) and \( I \) are the applied voltage and current respectively. \( \eta \) is the arc efficiency for the TIG welding process, \( v \) is the speed of torch travel in mm/s and \( t \) is the time in seconds. The parameters \( a, b \) and \( c \) are related to the characteristics of the welding heat source. The parameters of the heat source are chosen according to the welding conditions. This study is concerned with simulations of temperatures, displacements, stresses and strains in the elded structure without solid-state phase transformations using Marc software. In mechanical properties is same as used in the thermal analysis.

3. Results and discussions

In first calculation were studied at the same model to get an accurate result of temperature and residual stress in the welded plate. The main difficulty of the thermal field simulation in a welding process is Goldak model. Several cases of different parameters of heat distribution, heat input, and plate thickness have had their weld pool geometries analyzed and compared with each other as shown in figure 3. It is obvious some different from case to another. A 2D model is formulated in present work. The temperature dependent on thermos-physical and mechanical properties. The finite element is developed to validate the result. The predicted results are shown some differences in various cases.
the numerical simulations, Figure 4-8 show the residual stress distribution of the welded plate in x, y and z direction with different cases.

Figure 3. Residual stresses 2D plate in X, Y direction

Figure 4. Residual stresses 2D plate in X, Y (Case 1)

Figure 5. Residual stresses 2D plate in X, Y (Case 2)
4. Conclusions
In this study, the accuracy of the Goldak model parameters was investigated. Generally, the numerical simulation of the welding process is the prediction of residual stress. These cases showed that the methodology based on the finite element technique and Goldak model is a good proposal for welding cases when welding processes are employed. The parameters of the Goldak model have a significant influence on residual stress.
References

[1] R I Karlsson, B L Josefson 1990 *Journal of pressure vessel technology* **112** (1) 76  
https://doi.org/10.1115/1.2928591

[2] S Fricke, E Keim, J Schmidt 2001 *Nucl Eng Des* **206** (2) 139  
https://doi.org/10.1016/S0029-5493(00)00414-3

[3] M Siddique, M Abid, H F Junejo, R A Mufti 2005 *Mater Sci Forum* **13** 491  
https://iopscience.iop.org/article/10.1088/0965-0393/13/6/010/meta

[4] M Jonsson, L Karlsson, L E Lindgren 1995 *AWS Weld J, Weld Res Suppl* **64** (10) 301.

[5] P Dong 2003 *Welding in the world* **60** (2)  
https://link.springer.com/article/10.1007/s40194-015-0286-4

[6] Ruben L, Marina C, Maria A and Pedro M 2017 *Metals* **7** 136  
https://doi.org/10.3390/met7040136

[7] Wahab, M A, Painter, M J 1998 *Journal of Materials Processing Technology* **77** (1) 233  
https://doi.org/10.1016/S0924-0136(97)00422-6

[8] B Brickstad, B L 1998 *Int. J Pres Vessels Piping, 75* (1) 11  
https://doi.org/10.1016/S0308-0161(97)00117-8

[9] E M Qureshi, A M Malik, N U Dar 2015 *Advance in Mechanical Engineering* **1** 22  
https://doi.org/10.1155%2F2009%2F351369

[10] E F Rybicki, P A McGuire, E Merrick, J Wert *ASME J Press Vessel Technol*  
https://doi.org/10.1115/1.3264205 **104** (3) 204

[11] E F Rybicki, R B Stonesifer 1979 *Trans ASME J Press Vessel Technol*  
https://doi.org/10.1115/1.3454614 **101** (2) 149

[12] L Karlsson, M Jonsson, L E Lindgren, L M Nasstrom 1989 *American Society of Mechanical Engineers*  
http://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Altu%3Adiva-38656

[13] I Sattari Far, and Y Javadi 2008 *International Journal of Pressure Vessels and Piping* **85** (4) 265  
https://doi.org/10.1016/j.ijpvp.2007.07.003

[14] Z Wyman, Gary Zhuanga, R Halford 2001 *International Journal of Fatigue* **23** (1) 31  
https://doi.org/10.1016/S0142-1123(01)00132-3

[15] Y Dong 1997 *Welding Journal* **76** (10)  
https://www.osti.gov/biblio/562021

[16] W El-Ahmar 2007  
https://www.theses.fr/2007ISAL0023

[17] M Ziolkowski, H Brauer 2009 *The International Journal For Computation And Mathematics In Electric And Electronic Engineering* **28** (1) 140  
https://doi.org/10.1108/03321640910918940

[18] C S Wu, Q X Hu, J Q Gao 2009 *Computational Material Science* **46** (1) 167  
https://doi.org/10.1016/j.commatsci.2009.02.018

[19] J Goldack, A Chakravarti and M Bibby. 15 (2) 1984 299  
https://link.springer.com/article/10.1007/BF02667333

[20] D Klobcar, J Tusek, B Taljat 2004 *J. Comp. Mater. Sci.* **31** (3) 368  
https://doi.org/10.1016/j.commatsci.2004.03.022