Simulation of the residual stress in a multi-pass oil and gas pipe weld joint

Mahmood Hasan Alhafadhi¹, Gyorgy Krallics²

¹,²Institute of Physical Metallurgy, Metal Forming, and Nanotechnology, University of Miskolc, Hungary

E-mail: mahmoodhs199@gmail.com

Abstract. In this paper, a welding simulation procedure is developed using the FE software MSC Marc to predict the residual stresses. Numerical simulation was used to predict the thermal, mechanical and residual stresses behaviour in dissimilar material welded pipes which were found to be in good concurrence with experiments. Both two-dimensional FE model (2D) and three-dimensional FE model (3D) models are used to simulate the residual stresses in different directions in several regions of the weld zone under the same welding conditions. The 2D model was used to reduce the time and cost of numerical simulation. The aim of the present work is to understand the evolution of residual stresses (axial, radial and hoop stresses) in weldments. The results of the simulation reveal that the hoop and the axial residual stresses around the weld region are noticeably varying from those in the steady range.

1. Introduction

The research growth in the field of materials science, in general [1-8] and welding, in particular, is attracting great interest lately. The welding of materials which have independent thermal and mechanical properties leads to changes in residual stress. The multi-pass welding which has specific heat and equal periods are used for joining of thick metals. The areas near the weld zone undergo different heating and cooling cycles throughout the welding. Multi-passes 2D and 3D models for the welding are commonly used to examine the effect of residual stresses. The simulation for welding a pipe is always done using the multi-pass welding with element birth and death techniques. For arc welding process Marc packages are normally used [9-14].

The finite element (FE) simulation has become increasingly common for several predictions include residual stresses in welding pipe[15-23]. This study deals with the model implementation, which takes coupling phenomena of temperature evolution and hardness prediction during the welding. Therefore, the P460NH_1/E355K2 dissimilar welded materials joint are validated firstly, and then the residual stress state across the dissimilar welded joint is investigated and analysed. Based on the temperature fields and the residual stress induced by arc welding and avoiding the time of computation, a finer mesh is created at the weld zone, and a coarse mesh is created far away from the weld zone. In the 2D FE model, the total number of elements used is 8,466.
2. Model geometry and material properties

Figure 1 exhibit the geometrical shape and the sizes of the employed dissimilar welded pipe. The left pipe is P460NH_1 steel, and right pipe material is E355K2 steel, and the filler metal is Böhler. FE simulation of welding was performed on a dissimilar pipes have an outer diameter of D = 323.9 mm, a thickness of 11 mm, and a length of 450 mm as shown in Figure 1. The welding arc travelling direction and the welding start/stop position ($\theta = 0^\circ$) are also shown in Figure 1. The x-axis is the pipe length direction, the y-axis is the pipe thickness direction, and the z-axis is the pipe welding direction. The 3D model was made based on these elements. The cross-section of the weld is shown in Figure 1. The 2D FE model used instead of 3D with four-noded isoparametric solid. In this model, a fine mesh was used for the FZ and HAZ, and a coarse mesh was used in the region far from the weld. A mesh sensitivity study was carried out to investigate the reliance of FE mesh size on the precision of the examination results. The materials compositions are shown in Table 1. The welding parameters for weld joints are specified in Table 2. 2D model with linear four-node finite elements was developed to simulate the welding temperature field and residual stress allocation on P460NH_1/E355K2 dissimilar welded joint. In general, the 3D finite element used to analysis the heating and cooling cycle during the welding process, but it takes a very long calculation time.

![Figure 1. Three dimensional FE model and dimensions of analysis model and welding direction](image)

### Table 1. Chemical composition (wt%)

| Materials | C  | S  | P  | Mn  | Si  | Mo  | Ni  | Nb  | V   | Cr  | Cu  |
|-----------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|
| P460NH_1  | 0.2| 0.00| 0.02| 1.49| 0.33| 0.1 | 0.01| 0.05| 0.2 | 0.01| 0.03|
| E355K2    | 0.13| 0.01| 0.86| 0.86| 0.01| -   | -   | 0.02| 0.058| 0.02| 0.02|
| Böhler    | 0.1| -  | 0.02| 0.4 | 0.14| 0.5 | 0.15| -   | -   | 0.1 | 0.1 |

### Table 2. Welding parameters

| Pass No. | Current (A) | Voltage (V) | Speed mm/s | Efficiency | a (mm) | b (mm) | c_f (mm) | c_r (mm) |
|----------|-------------|-------------|------------|------------|--------|--------|----------|----------|
| 1        | 80          | 23.2        | 2          | 0.8        | 4      | 3      | 5        | 8        |
| 2        | 90          | 23.6        | 2          | 0.8        | 4      | 3      | 5        | 8        |
| 3        | 100         | 24          | 2          | 0.8        | 4      | 3      | 5        | 8        |
### 2.1. Double-ellipsoidal conical heat source model

Four nodes thermal and mechanical analysis elements were used for the analysis. The equation used for transient heat transfer during welding is given by

\[
p c \frac{\partial T}{\partial t(x,y,z,t)} = -\nabla \cdot q(x,y,z,t) + Q(x,y,z,t)
\]

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 inside heat rate, \( x, y \) and \( z \) are the coordinates in the system, \( t \) is time and \( \nabla \) is the spatial gradient operator. The various weld parameters in a double ellipsoidal distribution presented by Goldak et al as shown in Figure 2 [24].

![Graphical model parameters for the double-ellipsoid heat source](image)

Equations 2 and 3 show the distributions of the heat flux inside the front and rear quadrant of the heat source. The model is presented as a function of distance and time, together with several parameters that affect the heat flux magnitude and distribution.

The parameters of the heat source are chosen based on the welding conditions.

\[
q_f(x,y,z) = \frac{6\pi\eta f_f Q}{abc\pi^2} e^{-3\left(\frac{x}{a}\right)^2} e^{-3\left(\frac{y}{b}\right)^2} e^{-3\left(\frac{z}{c}\right)^2}
\]

\[
q_r(x,y,z) = \frac{6\pi\eta f_r Q}{abc\pi^2} e^{-3\left(\frac{x}{a}\right)^2} e^{-3\left(\frac{y}{b}\right)^2} e^{-3\left(\frac{z}{c}\right)^2}
\]

Where \( x, y, \) and \( z \) are the coordinates of the Goldak double ellipsoid model, \( \pi \) is the fraction of heat in the weld region, the heat input rate \( Q = \eta V I \) is calculated by welding parameters current (I), voltage (V) and \( \eta \) is the arc efficiency for the welding process, \( v \) is the speed of torch travel in mm/s, and \( t \) is the time in seconds. The factors \( f_f \) and \( f_r \) indicate the fraction of the heat, which are set up to attain the restriction \( f_f + f_r = 2 \). The parameters \( a, b \) and \( c \) are known the characteristics of the welding heat source.

### 2.2. Hardness test procedure (Experimental procedure)

The sample was polished after cutting from weld region (Figure 3.a and b), and the surface of the specimen was etched with HNO\(_3\) (nitric acid) 2% solution (nitrate etching agent) to show the passes and FZ and HAZ. The treated cross-section is shown in Figure 4.
The hardness measurement was carried out from top to bottom with 12 lines, the micrograph of the cross-section of weld section includes the hardness test measurement obtained by an optical microscope is shown in Figure 4 (a). The validation of the welding simulation procedure is carried out on a multi-pass weld with eight lines. The hardness measurement result at every 1 mm of distance along the weld centreline of the specimens, the effect of hardness distribution of weld joint presented by Maynier et al. [25] had developed a useful method to predict hardness.

The total hardness of steel is calculated depending on the volume fractions of the constituents of the microstructure:

\[
V = (FP\% \times HV_{F-P} + B\% \times HV_B + M\% \times HV_M) / 100
\]  

(4)

The hardness of the microstructures produced is given by:

\[
HV_M = 127 + 949C\% + 27Si\% + 11Mn\% + 16Cr\% Ni\% + 21\log v_R
\]  

(5)

\[
HV_B = -323 + 185C\% + 330Si\% + 153Mn\% + 144Cr\% + 191Mo\% + 65Ni\% +
\]

\[
(\log v_R)(89 + 53C\% - 55Si\% - 2Mn\% - 20Cr\% - 33Mo\% - 10Ni\%),
\]  

(6)

\[
HV_{F-P} = 42 + 223C\% + 535\%i + 30Mn\% + 7Cr\% + 9Mo\% + 12.6N\%i + (\log v_R)(10 -
\]

\[
19Si\% + 8Cr\% + 4Ni\% + 130V\%)
\]  

(7)

Where: \(v_R\) is the cooling rate in K/h; \(Hv\) is the hardness (Vickers); \(X_M, X_B, X_F\) and \(X_P\) are the volume fractions of martensite, bainite, ferrite and pearlite, respectively; \(HV_M, HV_B\) and \(HV_{F-P}\) are the...
hardness of martensite, bainite and the mixture of ferrite and pearlite, respectively. For the calculating of $HV_M$, $HV_B$ and $HV_{F+P}$ were used the formulae developed by Maynier et al. Figure 4 (b) shows the contours of temperature distribution across dissimilar welds joints obtained by the numerical simulation. The grey region of modelled cross-section denotes fusion zone where the temperature exceeds the melting point (1700 °C), and the colour lines indicate the fusion line and HAZ2 of the weld.

The results from the hardness test were used as part of the validation process of the numerical model developed in this work. The cross-section of the sample before the hardness test with three regions of welding and final hardness distribution is shown in Figure 5 a and b. Vickers hardness across FZ, HAZ and BM was carried out. The hardness of the FZ and HAZ (191–222 HV) were found to be considerably higher than that of the BM (about 326 HV). The hardness in the centre of the FZ is about 200 HV and linearly increases to about 305 HV in the HAZ during the welding process because the weld metal and the base metal which are close to the FZ are experienced cyclic thermal loads, the materials in this zone are subjected to plastic zone deformation. During the course mesh of weld zone of pipe, the material characteristics like the hardness of the FZ and the HAZ are highly correlated to the welding process, especially in multi-pass welding. Comparison of the axial residual stresses calculated with the 2D and 3D models are shown in Figure 5 (b).

3. Result and discussion

3.1 The results of the simulation with experimental hardness test

The hardness distribution from the simulation at the weld of the investigated dissimilar material with welding was calculated by using the rule of mixtures. Three lines were chosen to confirm the results and compare them with the predicted hardness simulation used MARC software. Figure 6 (a) shows the final hardness simulation distribution in weld cross-section. The hardness values measured were selected to compare across the weld joint at 2, 5 and 8 mm below the outer surface for the weld joint, as shown in Figure 6 (b). The hardness values measured 2 mm below the outer surface were found between 173 and 171 HV, whereas the hardness value for 5 mm below the outer surface was found to be between 180 to 209 HV. The third line of hardness test measured close to the inner surface was found to be ranging from 180 to 215 HV. The predicted hardness and the actual hardness was measured in HAZ2, it was higher than other regions. The hardness values progressively increase from base metal 1 to base metal 2 and minor increases in the hardness values were detected around the fusion zone followed by higher hardness values in HAZ 2.
3.2 Residual stresses distribution in the weld zone with a different direction

Figure 7, 8 and 9 (a) show the residual stress distribution in the weld zone. The residual stresses are predicted in all the regions, due to the variance in the temperature gradient, the material properties are given in the model for elevated stresses. Three types of residual stress were known as axial, radial and hoop stresses according to the coordinate system. The compression between stresses distributions are shown in Figure 7, 8 and 9 (b), the stresses near the cross-section weld zone and heat-affected zone change with distance along the weld zone, at the top of the cross-section weld zone, the axial stress distribution is shown in Figure 7 (b) which display more stress value in the weld area that gradually increased from base metal (BM1) to the base metal (BM2) end. Tensile hoop residual stress is developed at (HAZ1) and compressive stress at the (FZ) and (HAZ2). Figure 8 (b) shows the residual stress located in the centre of the cross-section weld zone, the maximum tensile and compressive axial stresses value are about -229 MPa and 820 MPa, respectively. The radial stresses along the weld zone are about 410 MPa, and compressive radial stress is -210 MPa. Compressive hoop stress value is about -300 MPa, and tensile hoop stress is 890 MPa. Figure 9 (b) shows the residual stress near the inner surface at the bottom of cross-section weld zone, the compressive axial stresses and hoop stresses are developed along weld zone and the maximum values are 780 MPa and 810 MPa. The radial stresses along the weld zone are almost constant.
4th International Conference on Rheology and Modeling of Materials (ic-rmm4)  
Journal of Physics: Conference Series  
1527 (2020) 012005  
doi:10.1088/1742-6596/1527/1/012005

Figure 8. Residual stress in the y-direction and residual stress in axial, radial and hoop direction

Figure 9. Residual stress in the z-direction and residual stress in axial, radial and hoop direction at the middle of the weld zone

4. Conclusion
This work shows the methodology of the simulation of welding. It presents the mock-up, the material properties and welding technologies that are needed to create a finite element simulation. Moreover, it describes how to build a correct finite element model in 2D to simulate the welding. Also, experiments were carried out so that hardness test measurements could be used to validate the 2D finite element model. The results show close agreement between simulated and experimental hardness in the weld. Therefore, the simulation methodology is acceptable, justifying the creation of a 3D model. The challenge here was to predict hardness test measurement using simulation of welding with dissimilar materials and also with multi-pass welding. The 2D pipe model obtained similar residual stress distribution with the 3D pipe model. While a significant difference in stress values for those two models can be observed.

References
[1] T Shchemelinina et al 2019 Építőanyag–JSBCM 71 (4) 131  
https://doi.org/10.14382/epitoanyag-jsbcm.2019.23
[2] J F M Ibrahim, A Mergen, E Ilhan Sahid, H S Basheer 2017 Advanced Ceramics Progress 3 (4) 1
[3] Emese Kurovics et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 613 012025  
https://doi:10.1088/1757-899X/613/1/012025
[4] J F M Ibrahim et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 613 012009  
https://doi:10.1088/1757-899X/613/1/012009
[5] J F M Ibrahim et al 2019 Építőanyag–JSBCM 71 (4) 120
https://doi.org/10.14382/epitoanyag-jsbcm.2019.21

[6] J F M Ibrahim, E Kurovics, L A Gömze 2019, MultiScience - XXXIII. microCAD International Multidisciplinary Scientific Conference, ISBN 978-963-358-177-3

[7] J F M Ibrahim, A. Mergen 2015 Diss. Marmara University.
https://doi.org/10.13140/RG.2.2.32693.32486

[8] MSC.Marc 2018.1 A: Theory and User Information

[9] R Ihara, T Hashimoto, M Mochizuki 2012 J. Phys.: Conf. Ser. 379 012050
https://doi.org/10.1088/1742-6596/379/1/012050

[10] M Abid, M Siddique, R A Mufti 2005 Modelling Simul. Mater. Sci. Eng. 13 455
https://doi.org/10.1088/0965-0393/13/3/013

[11] Anna M Pardowska, John W H Price, Trevor R Finlayson and R Ibrahim 2010 J. Phys.: Conf. Ser. 251 012050 https://doi.org/10.1088/1742-6596/251/1/012050

[12] Youfa Wu, Xiaohong Zhan, Haisong Yu, Xiaosong Feng and Peiyun Xia 2019 Mater. Res. Express 6 096515 https://doi.org/10.1088/2053-1591/ab2c4d

[13] D Akbari, I Sattari 2009 International journal of pressure vessels and piping 86 (11) 769 https://doi.org/10.1016/j.ijpvp.2009.07.005

[14] Hibbitt, D Hugh, V Pedro 1973 Computers & Structures 3 (5) 1145 https://doi.org/10.1016/0045-7949(73)90043-6

[15] Lindgren, E Hedblom 2001 Communications in numerical methods in engineering 17 (9) 647 https://doi.org/10.1002/cnm.414

[16] M Alhafadhi, G Kraklis, M Szűcs 2018 International Journal of Metallurgical & Materials Science and Engineering (IJMMSE) 8 (3) 1-12

[17] L Gao, Q Wang, L Y Bai , X H He 2019 IOP Conf. Ser.: Mater. Sci. Eng. 473 012013 https://doi.org/10.1088/1757-899X/473/1/012013

[18] M Alhafadhi, G Kraklis 2019 Machines. Technologies. Materials. 13 (10) 447 https://stumejournals.com/journals/mtm/2019/10/447

[19] Sz Szávai, Z Bézi, P Rózsahegyi 2016 Procedia Structural Integrity 2 10 https://doi.org/10.1016/j.prostr.2016.06.131

[20] Sz Szávai, Z Bézi, C Ohms 2016 Frattura ed Integrita Strutturale 36 36 https://neutronsources.org/files/e_residualstress_frompetten_2016.pdf

[21] M Alhafadhi and G Kraklis 2019 IOP Conf. Ser.: Mater. Sci. Eng. 613 012035 https://doi.org/10.1088/1757-899X/613/1/012035

[22] Dongwook Kim, Luca Quagliato, Wontaek Lee and Naksoo Kim 2017 J. Phys.: Conf. Ser. 896 012066 https://doi.org/10.1088/1742-6596/896/1/012066

[23] J Goldak, A Chakravarti, M Bibby 1984 Metallurgical transactions B 15 (2) 299 https://link.springer.com/article/10.1007%2FBF02667333

[24] Ph Maynier, B Jungmann, J Dollet Hardenability concepts with applications to steel 18 https://link.springer.com/chapter/10.1007/978-3-662-01596-4_11