Numerically simulated prediction of residual stresses in welding considering phase transformation effects

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Abstract. This work deals with investigating the effects of solid-state phase transformation on residual stresses during the welding of low carbon and high carbon steels. In this study, depending on MSC Marc code, the simulation considers the local microstructure properties changes due to the thermal welding cycles. A sequentially coupled thermal and mechanical 2-D finite element model (FEM) was used. In FEM, phase transformation temperature diagrams are used to anticipate the amount of martensite in the fusion zone (FZ), and heat affects zone (HAZ). The simulation results demonstrated that the residual stress in low carbon steel is not affected by the volume change caused by the austenite-martensite transformation. In contrarily, the residual stresses in the high carbon steel are considerably influenced by the martensitic transformation.

1. Introduction

Generally, the research interest in materials science [1-8] and particularly in welding is fast-growing recently. The weld failure can be assigned to many reasons, but one of the major cause is the residual stress resulted from phase transformation. During the welding, the size of the volumetric extension in the heat-affected zone (HAZ) and the fusion zone (FZ) relies on the amount of formed martensite. The phase transformation leads to change in the volume during heating and cooling rate. Some computational procedures have been developed to predict the residual stresses resulted from phase transformation [9-16]. Accurate prediction of the residual stress can enhance the quality of welding. The effectiveness of the numerical simulation method like (FEM) for analyzing the residual stress due to phase transformation in welding is reported in many works [17-20]. The finite element analysis package MSC Marc is used for simulating the phase transformation during welding [21].

2. Finite element model using for simulation

The residual stresses are examined by thermal and mechanical analysis using the finite element method. Two plates 25 x 500 x 1000 mm with single V-groove weld are butted-welded together. To accurately determine the residual stress in the welded model, a 2D finite element model was used with 5544 elements and 5954 nodes, as shown in Figure 1 (a) and (b). Three kinds of steel used for this work: low carbon steel highly alloyed (S690QL), low carbon steel low alloyed (S355J2G3), and high carbon alloyed steel (42CrMo4). The chemical compositions are shown in Table 1.
2.1. Heat source modelling and thermal analysis

In this work, four nodes thermal and mechanical analysis elements were applied for the analysis. The heat from the driving welding arc in the weld pool is used as a volumetric heat supplier with a Goldak Model [22]; this is represented by the following same equations. The parameters a, b, c_f, and c_r are connected to the shape of the welding arc. In the two equations, the origin of the coordinate system of welding is positioned at the centre of the welding arc, and the coordinate system is fixed to the weld line. In the finite element model using MSC Marc software, the welding arc moves in this fixed coordinate system. The parameters of the heat source are controlled to produce the required melted zone in the weld pool. A user subroutine models the heat source for the moving welding arc in MSC Marc are used for all materials with Eq. (1) and (2) (Table 2).

\[ pc \frac{\partial T}{\partial t}(x,y,z,t) = -\nabla \cdot q(x,y,z,t) + Q(x,y,z,t) \quad (1) \]

\[ Q(x,y,z,t) = \frac{6\sqrt{3}f_{\omega}f_{\eta}f_{\psi}}{abc\pi\sqrt{\pi}} e \left[ \frac{3f_{\omega}^{2}}{f_{\psi}} - \frac{3f_{\omega}^{2}}{f_{\eta}} - 3\left(\frac{z}{c}\right)^{2} - 3\left(\frac{y}{a}\right)^{2} \right] \quad (2) \]

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 rate, \( x \), \( y \) and \( z \) are the local coordinates in the reference system.
and $\nabla$ is the spatial gradient operator. The local coordinates are the double ellipsoid model, and $\pi$ is the amount of heat transfer 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 $c_f$ and $c_r$ are related to the characteristics of the welding heat source shown in Figure 2.

2.2 Mechanical Analysis and thermal properties

The same FEM are used with respective element types for analysis to correlate thermal and structural properties. The simulation cases S355J2G3, S690QL and 42CrMo4 respectively with the same welding condition in different cases. The thermal properties with all used material are shown in Figure 3, 4 and 5.

**Figure 3.** (a) Thermal conductivity and (b) specific heat capacity for 42CrMo4

**Figure 4.** (a) Thermal conductivity and (b) specific heat capacity for S690QL

**Figure 5.** (a) Thermal conductivity and (b) specific heat capacity for S355J2G3
The mechanical analysis is carried out by the same mesh as used in the thermal analysis. The studies are calculated by the thermal analysis using temperature history as the input parameters. Mechanical properties in dependence of the temperature are shown in Figure 6, 7 and 8, for different materials.

![Figure 6](image1.png)  
**Figure 6.** (a) Young's modulus and (b) Poisson's ratio for 42CrMo4

![Figure 7](image2.png)  
**Figure 7.** (a) Young's modulus and (b) Poisson's ratio for S690QL

![Figure 8](image3.png)  
**Figure 8.** (a) Young's modulus and (b) Poisson's ratio for S355J2G3

3. Result and discussion  
Residual stresses can change due to many factors, depending for instance on the physical and mechanical properties of the materials to be joined, the dimensions of the samples to be welded, the external constraints of the components to be welded, the heat input, the number of passes of the welding types. Three cases are presented to simulate the residual stress and to describe the effect of phase transformation on the residual stress for different carbon steels. The computed values of simulation, such as stress, will be plotted from the centerline weld to the end of the plate. Fig.10 and
11 show the simulated martensite and austenite distributions in the section of the finite element model with different cases. The martensitic transformation appeared in all cases, in various fractions due to differences in chemical compositions of S355J2G3, S690QL, and 42CrMo4. For steel 42CrMo4, the fraction of martensite transformation is more extensive than S690QL because of a relatively high carbon equivalent.

3.1 Comparison between two material (S690QL) and (42CrMo4)

![Figure 9](image1.png)

**Figure 9.** Martensite distribution in the cross-section of the plate: (a) low carbon steel highly alloyed (S690QL) (b) high carbon alloyed steel (42CrMo4)

![Figure 10](image2.png)

**Figure 10.** Austenite distribution in the cross-section of the plate: (a) low carbon steel highly alloyed (S690QL) (b) high carbon alloyed steel (42CrMo4)

3.2 Residual stress distribution with different direction in low carbon steel (high alloy S690QL)

Figure 11 reveals the residual stress distribution in case of low carbon steel (high alloy S690QL) with different direction shows the stresses for the welded zone is characterised by tensile stresses and compressive stresses at the heat-affected zone and base metal zone.

![Figure 11](image3.png)

**Figure 11.** Residual stress distribution in (S690QL) (a) the x-direction and (b) y-direction and (c) the z-direction
3.3 Residual stress distribution with a different direction in low carbon steel (low alloy S355J2G3)
Figure 12 shows the result shows that the residual stress distribution in low carbon steel (low alloy S355J2G3) with different direction and also shows the stresses in different region.

![Image](a) (b) (c)

**Figure 12.** Residual stress distribution in (S355J2G3) (a) the x-direction and (b) y-direction and (c) the z-direction

3.4 Residual stress distribution with a different direction in high carbon (42 CrMo4)
Figure 13 the result shows that the residual stress distribution in case of high carbon (42 CrMo4) with different direction and shows the stresses tensile stresses and compressive stresses in the welded zone, heat-affected zone and fusion zone.

![Image](a) (b) (c)

**Figure 13.** Residual stress distribution in (42 CrMo4) (a) the x-direction and (b) y-direction and (c) the z-direction

3.5 Residual stress on the outer surface of the plate

![Image](a) (b) (c)

**Figure 14.** Residual stress outer surface in (a) the x-direction (b) the y-direction and (c) the z-direction
Figure 14 shows the residual stress on the outer surface in a different region. The maximum value of the residual stress in the x-direction in high carbon (42 CrMo4) can be clearly seen while in y and z-direction the maximum amount of low carbon steel (low alloy S355J2G3) is observed.

4. Conclusion
A 2D finite element model considering phase transformation is developed to analyze the arc welding process and to simulate the residual stress. The method is applied to predict the residual stress in both high carbon steel and low carbon steel. According to the present simulation results, when the residual stresses with different amount of steel are predicted using numerical simulation, it is necessary to consider phase transformation. For high carbon steel, phase transformation has a significant effect on the residual welding stress. The results presented the residual stress distribution with different cases of the amount of carbon. The analysis of the results showed that accurate residual stress predictions can be made with the changes of phase transformation.

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 İllhan Sahin, 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:10.1088/1742-6596/613/1/012025
[4] J F M Ibrahim et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 613 012009 https://doi:10.1088/1742-6596/613/1/012009
[5] J F M Ibrahim et al 2019 Építőanyag–JSBCM 71 (4) 120
[6] https://doi.org/10.14382/epitoanyag-jsbcm.2019.21
[7] J F M Ibrahim, E Kurovics, L A Gömze 2019 MultiScience - XXXIII. microCAD International Multidisciplinary Scientific Conference, ISBN 978-963-358-36-3
[8] J F M Ibrahim, A. Mergen, 2015 Diss. Marmara University. https://doi.org/10.13140/RG.2.2.32693.32486
[9] M Alhafadhi, G Krallics 2019 Machines. Technologies. Materials 13 (10) 447 https://stumejournals.com/journals/mtm/2019/10/447
[10] Sz. Szávai, Z Bézi, P Rózsahegyi 2016 Procedia Structural Integrity 2 10-23 https://doi.org/10.1016/j.prostr.2016.06.131
[11] Sz Szávai, Z Bézi, C Ohms 2016 Frattura ed Integrita Strutturale 36 36 https://neutronsources.org/files/_e__residual_stress_from_petten_2016.pdf
[12] Güven İpekoğlu, Tevfik Küçükümeroğlu, Semih M Aktarer, D Murat Sekban and Gürel Çam 2019 Mater. https://doi.org/10.2478/ajmse-2019-0010
[13] M Abid, M Siddique and R A Mufti 2005 Modelling Simul. Mater. Sci. Eng. 13 455 https://doi.org/10.1088/0965-0393/13/3/013
[14] M Alhafadhi, G Krallics, M Szűcs 2018 International Journal of Metallurgical & Materials Science and Engineering (IJMMSE) 8 (3) 1-12
[15] M Alhafadhi and Gyorgy Krallics 2019 IOP Conf. Ser.: Mater. Sci. Eng. 613 012035 https://doi.org/10.1088/1742-6596/613/1/012035
[16] H. L. Jaber, M. Pouranvari, S. P. H. Marashi, M. Alizadeh-Sh, R. K. Salim , F. A. Hashim 2014 Science and Technology of Welding and Joining 19 (7) 565-571 https://doi.org/10.1179/1362171814Y.0000000226
[17] A M Paradowska, J W H Price, T R Finlayson, U Lienert, P Walls and R Ibrahim 2009 J. Phys.: Condens. Matter 21 124213 https://doi.org/10.1088/0953-8984/21/12/124213
[18] D Sebayang, YHP Manurung, A Ariri, O Yahya, H Wahyudi, AK Sari and D Romahadi 2018 IOP Conf. Ser.: Mater. Sci. Eng. 453 012020 https://doi.org/10.1088/1742-6596/453/1/012020
[19] L Gao, Q Wang, L Y Bai and X H He 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **473** 012013  
https://doi.org/10.1088/1757-899X/473/1/012013

[20] R X Bai, Z F Guo and Z K Lei 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **281** 012032  
https://doi.org/10.1088/1757-899X/281/1/012032

[21] MSC.Marc 2018.1 *A: Theory and User Information* pp. 270-272

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