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Research Article

Investigating The Residual Stresses, The Deformations and The Temperature Distribution During Angular Hard Facing of Mild Steel

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Abstract

In this study, permanent stress and deformations resulting from angular weld seams of the hardfacing process in flat plates were investigated. Temperature distributions, stress distributions, and permanent deformations were calculated in the study carried out with the finite element method. Experiments in the literature were used for validation. A very high agreement was obtained between the experimental and model results. Since only longitudinal and transverse welds were examined in previous studies, how angular welds will affect stress and deformations has been demonstrated in this study. In addition, the changes in stresses were calculated considering the cooling time after the welding process. Among the findings, it has been observed that long weld seams cause higher temperatures, deformations, and stresses. In addition, after cooling, it is seen that the stresses increase even more in terms of both tension and compression.

Keywords: FEM, Hardfacing, Welding.

İmalat Çeliğinin Açısal Sert Dolgu Prosesinde Artık Gerilme, Deformasyon ve Sıcaklık Dağılımının Sonlu Elemanlar Metoduyla İncelenmesi

Öz

Bu çalışmada, düz plakalardaki sert dolgu prosesinin açısal kaynak dikişleri sonucunda oluşan kalıcı gerilme ve deformasyonlar incelenmiştir. Sonlu elemanlar yöntemiyle yapılan çalışmada sıcaklık dağılımları, gerilme dağılımları ve kalıcı deformasyonlar hesaplanmıştır. Doğrulama maksadıyla literatürdeki deneyler kullanılmıştır. Deneysel ve model sonuçları arasında çok yüksek bir uyum elde edilmiştir. Daha önceki çalışmalarda sadece boyuna ve enine kaynak dikişleri incelendiğinden, açısal kaynak dikişlerinin gerilme ve deformasyonlara nasıl etki edeceği bu çalışmada ortaya konmuştur. Ayrıca kaynak prosesi sonrasında soğuma zamanı dikkate alınarak gerilmelerdeki değişiklikler de hesaplanmıştır. Bulgular arasında; uzun kaynak dikişlerinin daha yüksek sıcaklıklara, deformasyonlara ve gerilmelere neden olduğu görülmüştür. Ayrıca soğuma sonrasında gerilmelerin hem çekme hem de basma anlamında daha da arttığı görülmektedir.

Anahtar Kelimeler: Sonlu elemanlar yöntemi, Sert dolgu, Kaynak.

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1. Introduction

Welding simulations have been taking place in the field of manufacturing studies in the late decades. Transient thermal studies have been performed after the 1980's by the Goldak moving heat input method (Goldak et al., 1984). Goldak et al. improved a different geometrical heat input model to simulate transient heat transfer in both thin and thick plates (Goldak et al., 1984). Beforehand the Gaussian moving heat input model was used and this model was not so successful in simulating the temperature history of the welding process. Arora et al. used the Goldak heat input to investigate the Submerged Arc Welding of mild steel (Arora et al., 2019). Different thickness, welding speed, and amperage values of plates were modeled and the temperatures very close to the experimental ones were obtained. Maximum distortion in the flat plates was 3 mm. Deformations in butt-welded plates were investigated by Chen et al. (Chen et al., 2014). They also utilize Goldak heat input in order to simulate the moving heat source. Material properties were given as temperature-dependent. By doing so, the temperature history was well predicted by the model. Three thermocouples close to the weld centerline were utilized to measure the temperature history. 300 MPa tensile stress and 4.5 mm distortion was calculated by the model which is very close to the experimental results.

Ghosh and Chattophadyaya studied different geometrical heat input models in simulating heat input during welding (Ghosh & Chattopadhyaya, 2010). Their model was a conical Gaussian model. They compared the analytical solution for the semi-infinite plate with the 2D and 3D FEM solutions. Both the 2D and 3D solutions gave good results. Hashemzadeh et al. also studied different heat source models (Hashemzadeh et al., 2014). In thin plates, semi ellipsoidal and double ellipsoidal models predicted the residual stresses better than the Gaussian heat source.

Prasad et al. investigated the pipe welds and calculated the residual stresses after the welding process (Varma Prasad et al., 2016). Their structural calculation took into account the thermal strain, elastic and plastic strains. 200-ampere TIG welding caused a maximum of 300 MPa tensile stresses and 420 MPa compressive stresses on the outside of the pipe.

Xavier et al. studied the microstructure changes after welding with the help of Goldak heat input (Xavier et al., 2015). Their predictions were in accordance with the experiments they performed.

Zubairuddin et al. studied multi-pass welding simulation (Zubairuddin et al., 2017). They showed that the model considering the metallurgical changes can predict the residual stresses better than the other models.

Kaptanoğlu et al. worked on hardfacings and predicted the optimal process parameters for the Submerged Arc Welding process (Kaptanoğlu et al., 2016). Lazic et al also studied the hardfacing process (Lazić et al., 2016). Their experimental results showed that the tempering after hardfacing can be helpful to decrease the residual stresses. Lazic et al studied in another work the deformations occurring after the hardfacing process (Lazic et al., 2015). Savas has studied the longitudinal welding patterns in hardfacing (Savaş, 2021a). The results showed detrimental deformations in a 2 mm thick plate. Zargar et al. investigated the effect of patterns in hardfacing (Zargar et al., 2016). They studied the Submerged Arc Welding of corner joints. Günay et al. analyzed the influence of transverse welding seams on the residual stress of fillet welds (Günay et al., 1997).

In the present work, the effects of angular welding seams on the distortions and residual stresses were investigated.

2. Material and Method

2.1. Welding Simulation

The temperature distribution calculated for the welding process took into account the conduction, convection, and radiation. The stress and deformation calculation of the model deals only with the elastic, plastic, and thermal strains, but not the metallurgical effects. The temperature-dependent material properties of St37, are not tabulated in this text, please refer to reference (Chen et al., 2014). The mobile heat input model was taken as a different geometrical model which is the Goldak heat source model. The joining variables which are utilized in the simulation are tabulated in Table 1(Chen et al., 2014). The Goldak mobile heat input style is shown in Figure 1. In present numerical work, the temperature part and the stress part are mutually coupled.

Table 1. The Goldak heat input values for the joining analysis.

a (distance in the x-axis)	5 millimeters
b_f (distance in the y-axis, fore)	5 millimeters
br (distance in the y-axis, back)	15 millimeters
c (distance in the z-axis)	5 millimeters
f_f (fore fragment)	0.5
f_r (back fragment)	1.5
Joining velocity	8.33 mm/sec
Potential difference, U	27 Volts
Amperage, I	125 Amperes
Effectivity, η	0.9
Energy inlet, Q= ηIU	3037.5 Watts

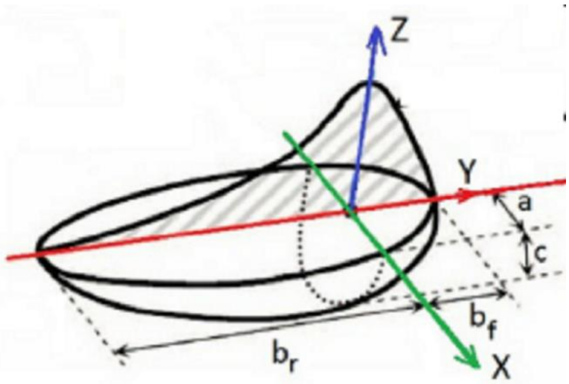


Figure 1. The geometrical style for the Goldak heat input.

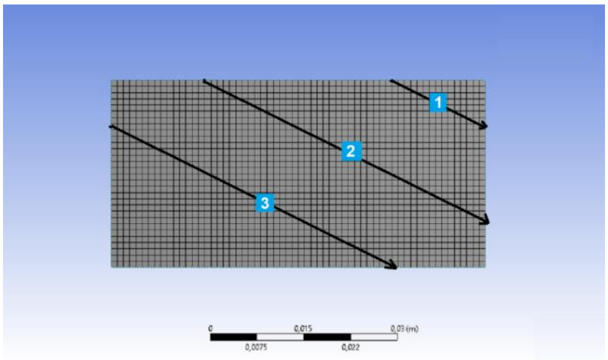
2.2. Numerical Model

Angular hardfacing patterns are shown in Figures 2a and 2b. Weld seams in Figure 2a have an angle of 26 degrees with the longitudinal side of the plate whereas weld beads in the other figure have an angle of 63 degrees with the long edge. The total weld seam length is kept constant at 117 mm in order to equalize the heat input (which is 41.4 KJ). The welding conditions used are 22 V, 100 A, and 5.6 mm/s. In Figures 2a, and 2b the mesh created for the ANSYS FEM model can also be seen. One path is used where residual stresses are given linearly (see Figure 3). The two-part Goldak moving heat input model is specified in the equations below (Savaş, 2021a):

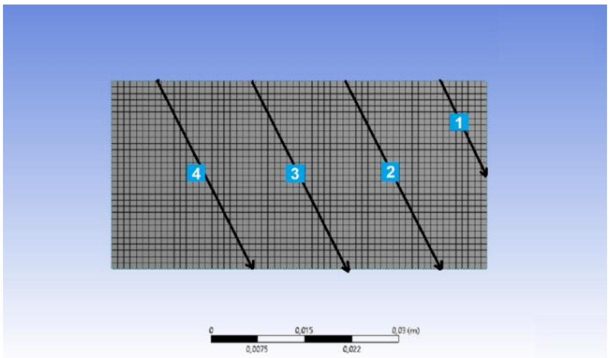
$$q_f(x,y,z) = \frac{6\sqrt{3}(f_f Q)}{ab_f c\pi\sqrt{\pi}} exp\left(-\frac{3x^2}{a^2} - \frac{3y^2}{{b_f}^2} - \frac{3z^2}{c^2}\right) \quad (1)$$

$$q_r(x,y,z) = \frac{6\sqrt{3}(f_r Q)}{ab_r c\pi\sqrt{\pi}} exp\left(-\frac{3x^2}{a^2} - \frac{3y^2}{{b_r}^2} - \frac{3z^2}{c^2}\right) \quad (2)$$

Here q_f is the front of the heat source and qr is the back. Convective heat transfer and radiation emission coefficient were used respectively as follows: 10 W/m2/K and 0.8. The ambient temperature is assumed to be 22 °C. Four corners of the sheets were held fixed. ANSYS time-dependent analysis was performed to obtain deformations and stresses. Temperature-dependent material properties are coded in the command section of ANSYS. The element type is SOLID 226 and the elements are geometrically hexahedral. The 2 mm thick plates have cell dimensions of 1x1x1 mm. Large deformations are taken into account.



2a.



2b.

Figure 2. Angular welding patterns, a. 26 degrees patterns, b. 63 degrees patterns.

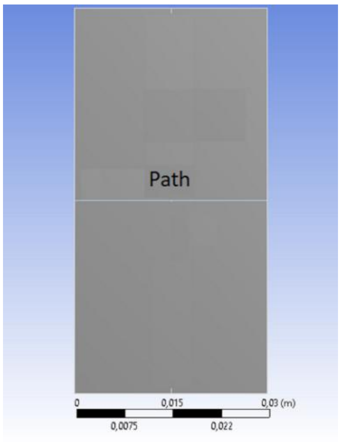


Figure 3. Path

The total strain can be given by the following equation:

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{thermal} \quad (3)$$

2.2. Validation

To validate the FEM model, a plate was modeled in ANSYS and the welding process was simulated. The measurements of the plate are 300 × 150 × 4 mm and are the same as experiment 1 in the study of Chen et al.(Chen et al., 2014). When the temperature distribution is compared with the test results under the same conditions (see Table 1) in the article; the highest temperatures of the number 1 thermocouple and its corresponding model in the experiment were found to be 450 and 444 °C, respectively, the highest temperatures of the number two thermocouple and the model are 248 and 238 °C, finally, both the third thermocouple and the model highest temperatures are165 C. As can be seen from these values, the highest error is 4%. The verification of the structural part was also done according to the same experiment. While the maximum deformation of the butt-welded plate is 4.5 mm in the test, it is 3.5 mm in the 4 mm plate model. This makes a 22 percent error. According to the same test, the longitudinal stress along the weld centerline is 328 MPa. The current model estimates the longitudinal stress at 312 MPa. The error percentage is 4.8. Considering the values here, it is evaluated that the current simulation can be used to guess the temperature distribution, deformations, residual stresses.

3. Results and Discussion

The longitudinal weld seams in hardfacing were investigated by Savaş (Savaş, 2021a, 2021b). The results of these studies showed that straight patterns and preheating can cause better results in the sense of distortions. GTAW process was also investigated by Savaş (Savaş, 2020). His findings show that diverging welding seams can cause better results in the sense of deformations and residual stresses. The angular welding patterns in hardfacing application was studied by this present work. 26 and 63 degrees' angles were chosen to be analyzed. The long side of the hardfaced plate makes these angles with the weld seams. Their effects on the deformation field and temperature field were investigated by Figures 4 and 5. In Figure 4a approximately 3 mm maximum deformation was observed. That much distortion in a 2 mm thick plate is very crucial. The distortion takes place on the right-hand side of the plate. In Figure 4b the maximum distortion can be calculated as 2.2 mm. Figure 5a shows that the maximum temperature is 2630 C. In Figure 5b the maximum temperature goes down to 2450 C. This can be explained by the fact that the long seams cause more conduction and less convection rather than the short seams. The decrease of distortion from 4a. to 4b. can also be explained by the same reason.

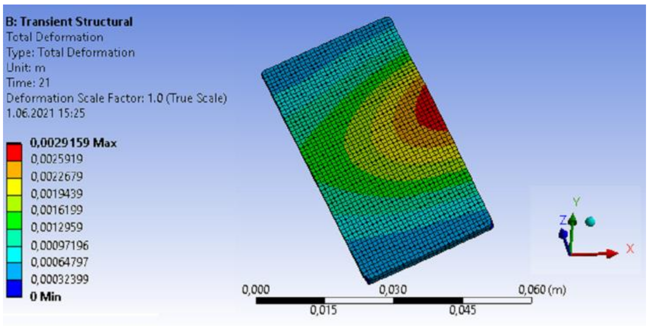


Figure 4a. Total deformation at the 21st second (26 degrees' weld seam).

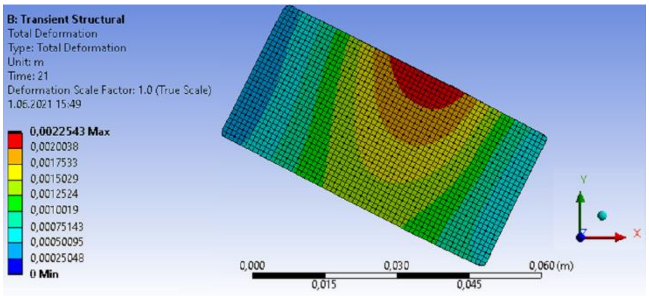


Figure 4b. Total deformation at the 21st second (63 degrees' weld seam).

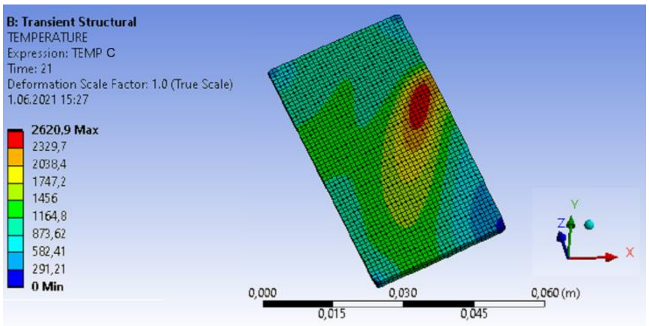


Figure 5a. Temperature distribution at the 21st second (26 degrees' weld seam).

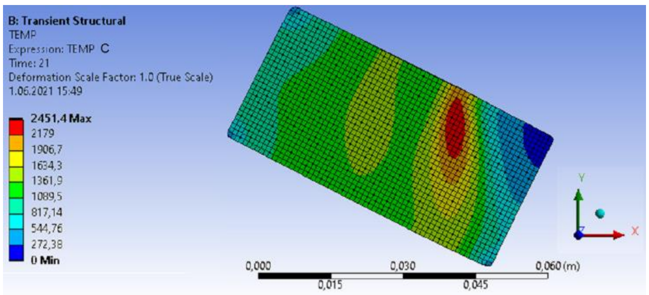


Figure 5b. Temperature distribution at the 21st second (63 degrees' weld seam).

Figure 6 shows the x-direction and y-direction stresses along the path defined in Figure 3. The solid lines depict the situation just after the welding process (after 21 seconds), whereas the dashed lines show the stresses after 60 seconds of cooling time.

Maximum tensile stress occurs after cooling in the x-direction while welding in the weld seam which is making 63 degrees with the y-axis. Y-axis stress after cooling with the 26 degrees weld seam follows the highest tensile stress. The highest compressive stress was calculated after the cooling period in again y-axis and 26 degrees weld angle. The second highest compressive stress was obtained in the y-axis and 63 degrees angle. Just after the welding without waiting for the cooling time the y-axis stress with 26 degrees is the highest in both tensile and compressive senses.

Lazic et al. (2015, 2016) have studied the influence of plate thickness on the residual stresses and deformations. They concluded that thick plates can be affected less likely by the hardfacing process. They also stated that heat treatment can significantly reduce the residual stresses.

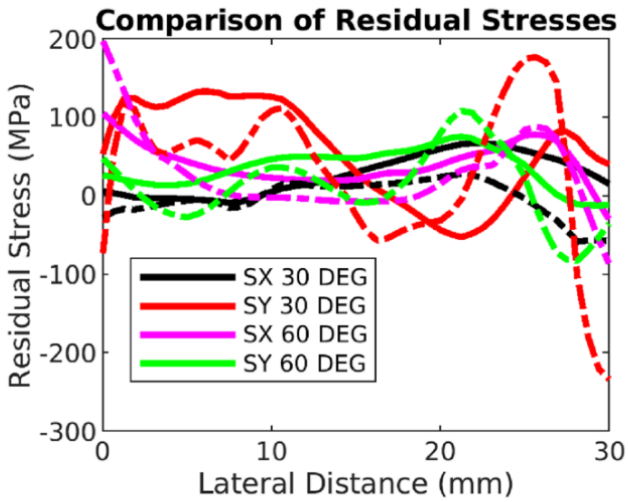


Figure 6. Comparison of residual stresses.

4. Conclusions and Recommendations

The welding simulation for the angular hardfacing of mild steel was performed. The structural and thermal parts were solved simultaneously. The experiments from the literature were utilized in order to validate the welding simulation. The predicted temperatures, deformations, and residual stresses show that this model can be utilized to analyze the angular hardfacing of mild steel. The results of the model show that long welding seams can cause high temperatures, high distortions. The welding seam which is making 26 degrees with the long edge of the plate has longer distances of weld passes. Therefore, for this model, the temperatures and deformations are bigger than the other model. After cooling, it is observed that the residual stresses are getting higher. In order to minimize these stresses a kind of tempering process is needed.

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