Numerical and Experimental Investigation into Effect of Temperature Field on Sensitization of AISI 304 in Butt Welds Fabricated by Gas Tungsten Arc Welding

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This study examines the effect of the temperature field on the sensitization tendencies of AISI 304 two-pass butt welds fabricated using the gas tungsten arc welding (GTAW) method. The thermal cycles induced in the two-pass welding process are simulated using ANSYS software based upon a moving heat source model and the function of Element Birth and Death was employed also in the filled metal GTA welding. The validity of the numerical model is confirmed by comparing the simulation results with the corresponding experimental results. The results show that the heat-affected zone (HAZ) in the 2nd pass specimen is susceptible to intergranular corrosion (IGC). However, the HAZ in the 1st pass specimen shows no obvious signs of IGC. The difference in the sensitization tendencies of the two specimens is attributed to a difference in their respective heating and cooling times.


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1. Introduction

AISI 304 stainless steels are widely used throughout the chemical, petrochemical and nuclear power industries due to their favorable mechanical, fabrication and corrosion resistance properties. In practice, most applications of AISI 304 stainless steel require the welding of two or more components. The welding process is generally accomplished using multi-pass welding methods such as gas tungsten arc welding (GTAW). However, the rapid heating and cooling effects produced during the welding process may result in intergranular corrosion (IGC) in the heat-affected zone (HAZ) as a result of the precipitation of chromium-rich M23C6 carbides at the grain boundaries. The literature contains many investigations into the susceptibility of austenitic stainless steels to IGC (referred to as sensitization) following isothermal exposure or continuous cooling. The time-temperature-sensitization (TTS) and critical cooling rate (CCR) diagrams provide the means to predict the sensitization behavior during continuous cooling/heating. However, they are inapplicable to the sensitization produced during welding, especially in multi-pass welding processes, in which sensitization occurs not as a result of continuous cooling/heating, but as a result of repeated heating and cooling through the sensitization range. Therefore, in understanding the origins of the sensitization effect, it is necessary to perform experimental welding tests in order to determine the time required for sensitization and the temperature range over which sensitization occurs.

The sensitization of austenitic stainless steel depends on the alloy content (particularly the carbon content), the grain size, the prior deformation and the characteristics of the welding thermal cycle. Solomon reported that in the continuous cooling sensitization of AISI 304 stainless steel, the peak temperature from which continuous cooling results in sensitization increases with an increasing carbon content. Moreover, Garcia et al. showed that prior working increases the cooling rate required to produce sensitization. Various studies have shown that deformation accelerates the development of sensitization in stainless steel, for the corresponding strain increases both the carbide growth kinetics and the extent of chromium diffusion. ASTM 262 prescribes various standard practices for detecting the susceptibility of austenitic stainless steels to intergranular corrosion attack. Various Laser De-sensitization Treatment (LDT) techniques have been proposed for altering/reparing the IGC of weldments, e.g. Laser Surface Melting (LSM) and Laser Shot Peening (LSP). However, in order to desensitize the weldment, it is first necessary to know the size and range of the sensitization region. In fact, in the vast majority of cases, IGC occurs in the heat-affected zone (HAZ) in type 304 stainless steels subjected to temperature in the range of approximately 400 to 800°C. Thus, to improve the resistance of AISI 304 stainless steel weldments to IGC, we need a detailed understanding of the effect of the welding-induced temperature field on the sensitization tendency of the weldment.

However, welding is a highly complex physical phenomenon influenced by many parameters, including the heat transmission mode (i.e. conduction, radiation and convection), the geometry and properties of the workpiece, the phase transformations caused by the heat input in the welding procedure, and so on. Furthermore, the welding performance is significantly dependent upon the welding parameters. Thus, analytical methods are limited in their ability to clarify the physical phenomena which take place during a typical welding operation. As a result, the use of some form of numerical modeling approach is generally preferred. Among the various numerical modeling schemes available, the Finite Element Method (FEM) tends to be the most widely used due to its accuracy and compatibility with commercial software.

The present study develops a 3-D finite element (FE) thermal model of the temperature field induced within an AISI 304 butt weld fabricated using a two-pass GTAW welding process. The validity of the numerical model is...
demonstrated by comparing the simulation results with the corresponding experimental results. The results provide useful insight into the sensitization tendencies of the AISI 304 weldment during the two welding passes. Specifically, the results enable the temperature and duration required for sensitization to be identified for each pass. Moreover, the results enable the range and size of the sensitization zone to be predicted, and thereby provide the information required to accomplish desensitization using LSM or LSP methods.

2. Theoretical Model

2.1 Theoretical foundation

In constructing a theoretical model to predict the thermal history of the HAZ of the GTAW weldment during the welding process, the following assumptions are made:

1. the workpiece material (AISI 304) has an austenitic microstructure and undergoes no phase transformation during welding.
2. the thermal history of the HAZ is determined by the effects of conduction, convection and radiation. The coefficients of convection and radiation between the workpiece and the environment are assumed to be constant.
3. the weldment is symmetrical, and thus the simulations need consider only one half of the FE model.
4. in this paper, we mainly investigate the thermal affect in HAZ of AISI 304 welding, so the effects of the electric magnetic field in the GTAW process are not discussed.

2.2 Mathematical model of heat transmission during welding process

The distribution of the temperature field induced during welding can be expressed by the energy balance equation. In modeling the heat transmission during welding, the effects of weld pool stirring are ignored. Moreover, k is assumed to be isotropic in all directions. The steady-state heat flow can be modeled using the following energy balance equation:

\[
\rho C \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\partial k}{\partial T} \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 + \left( \frac{\partial T}{\partial z} \right)^2 + \dot{Q}_G, \tag{1}
\]

where \( \rho \) is the density (kg m\(^{-3}\)), \( C \) is the specific heat (J kg\(^{-1}\)K\(^{-1}\)), \( T \) is the temperature (K), \( t \) is time (s), \( k \) is the thermal conductivity (W m\(^{-1}\)K\(^{-1}\)), \( \dot{Q}_G \) is the rate of heat generation or consumption per unit volume (W m\(^{-3}\)).

2.3 Construction of welding model

The analysis performed in this study considers the butt welding of two thin AISI 304 plates of equal size. During the welding process, the sheets are placed on a stationary work plane with a fixed coordinate system \((x, y, z)\), as shown in Fig. 1. The heat source (a tungsten pole) is modeled using a Gaussian distribution. During the welding process, the heat source moves continuously in the x-direction of the work plane at a constant velocity \( u \). Thus, the heat supplied to the weldment can be modeled as \( q(\xi, y, z) \), in which \( \xi = x + ut \).

The corresponding heat transmission can then be computed from eq. (1).

2.4 Welding heat source and boundary conditions

In modeling the GTAW welding process, it is assumed that the moving electric arc induces a double ellipsoid heat source distribution within the weldment.

The boundary conditions in the mathematical welding model comprise the initial conditions and the natural boundary conditions. The two conditions are given as follows:

2.4.1 Initial conditions

\[
T(x, y, z, 0) = T_0(x, y, z). \tag{2}
\]

2.4.2 Natural boundary conditions

\[
k_n \frac{\partial T}{\partial n} + h_c(T - T_0) + \sigma \varepsilon (T^4 - T_0^4) = 0, \tag{3}
\]

where \( k_n \) is the thermal conductivity normal to the surface (W m\(^{-1}\)K\(^{-1}\)), \( h_c \) is the heat transfer coefficient for convection (W m\(^{-2}\)K\(^{-1}\)), \( T_0 \) is the atmospheric temperature for convection and/or radiation, \( \sigma \) is the Stefan-Boltzmann constant (W m\(^{-2}\)K\(^{-4}\)), and \( \varepsilon \) is the radiation emissivity.

3. Experimental Procedure and Numerical Simulations

3.1 Materials and welding experiments

The welding trials were performed using commercial grade AISI 304 stainless steel in the form of 3 mm thick rectangular plates. Note that commercial grade AISI 304 was specifically selected since it is used in a wide variety of industrial applications and shows most of the rolling characteristics related to IGC. The chemical composition of the as-received AISI 304 plates is summarized in Table 1. The plates were machined into specimens measuring 70 \( \times \) 150 mm\(^2\) (length \( \times \) width) and were then polished using 600-grit SiC paper to remove any oxidized film and/or impurities from the surface. Finally, the plates were degreased using an acetone solution.

As shown in Fig. 1, the GTAW butt welds comprised two beveled AISI 304 plates clamped in such a way as to form an 80° V-groove with no root opening gap and a 1 mm root face. The weldments were fabricated using a two-pass direct current electrode negative (DCEN) GTAW process. The inter-pass temperature was specified as <50°C. The welding
process was performed using AISI 308 filler metal wire with a core diameter of 1.6 mm. The composition of the filler wire, as determined in accordance with AWS E308-16, is summarized in Table 2. The welding passes were conducted using the process parameters shown in Table 3 with a pure argon (99.9%) shielding gas in both cases.

The temperature distribution within the GTAW weldments was measured continuously throughout the welding process using K-type thermocouples with a diameter of 0.254 mm (AWG No. 30). Figures 2(a) and (b), show the critical positions of sensitization temperature (blue notations). The thermocouples were attached to the lower surface of the weldment in order to shield them from the heat radiated by the welding heat source. Moreover, the thermocouples were arranged such that localized temperature gradients and thermal histories could be computed within three specific regions of interest in the weldment, namely the carbide solubility zone, the weld decay zone, and the base metal. The thermocouple outputs were sampled every 100 ms and were saved to a PC for further processing.

The corrosion resistance properties of the 1st and 2nd pass GTAW weldments were investigated by immersing the weldments in a 10% oxalic acid solution and etching the surface at 1 A/cm² for 1.5 min (ASTM 262 Practice A). The surfaces of the etched specimens were then observed using SEM in order to check for the occurrence (or nonoccurrence) of IGC.

### 3.2 Numerical simulation of GTAW welding process

The temperature field induced during the GTAW welding process was simulated using ANSYS software (Version 11.0) with the time-step parameters given in Table 3 and the FE model presented in Fig. 3. The model was constructed using both four- and eight-nodal thermal conduction solid elements. Specifically, a fine mesh (eight-nodal elements) was used in the regions of the weldment subject to a higher temperature gradient (i.e. close to the welding line), while a coarse mesh (four-nodal elements) was applied elsewhere. The mesh comprised a total of 8640 elements and 22587 nodes. In performing the simulations, the transient temperature field was simulated using the Element Birth and Death function. The ambient temperature and initial workpiece temperature were both specified as 20°C and the convection coefficient between the weldment and the environment was assumed to be 60 J·C⁻¹·m⁻²·s⁻¹. Finally, the temperature-dependent physical properties of the AISI 304 plates and AISI 308 filler metal were specified in accordance with the data shown in Table 4, which are taken directly from the JMatPro database.

### 4. Results and Discussions

#### 4.1 Microstructural examination following oxalic acid etch test

Figure 4 presents SEM images of the 1st and 2nd pass GTAW weldments following the oxalic acid etch test. As shown, the weldments comprise four characteristic regions,
Fig. 4 (a) SEM photographs showing microstructure at various locations in 1st pass GTAW weldment following oxalic acid etch test, and (b) Experimental results for peak temperature profiles vs. 2nd pass GTAW weldment following oxalic acid etch test.
namely the fusion zone (FZ), the carbide solubility zone (CSZ), the weld-decay zone (WDZ), and the base metal (BM). The SEM images corresponding to the three rectangular areas marked in Fig. 4(a) show that the CSZ, WDZ and BM regions of the 1st pass weldment have a step structure. In other words, the 1st pass weldment shows no obvious signs of IGC. Meanwhile, the images corresponding to the three rectangular areas indicated in Fig. 4(b) show that the WDZ of the 2nd pass weldment has a ditch structure, while the CSZ region of the 2nd pass weldment has a lower susceptibility to IGC than the WDZ of the 2nd pass weldment is affected by IGC. The sensitization range within which Cr-carbide precipitation occurs, and thus the sensitization range in the current 2nd pass weldment has a width of around 7.5 mm (\( \Delta z = 5.5 \sim 13 \) mm), while that in the 2nd pass weldment has a width of approximately 8.5 mm (\( \Delta z = 6.5 \sim 15 \) mm).

4.3 Temperature history of HAZ in different regions of weldment

Figures 6(a) and (b) present the experimental and simulation results for the thermal cycles at each of the seven measurement positions on the 1st and 2nd pass GTAW weldments, respectively. Observing the temperature profiles at measurement positions \( T_{G11} \) and \( T_{G12} \) (Fig. 6(a)), and \( T_{G21} \) and \( T_{G22} \) (Fig. 6(b)), located in the CSZ region of the two weldments (see inset), it can be seen that the maximum experimental temperatures are 1367.7 and 1070.7°C (Fig. 6(a)), and 1294.3 and 1122.9°C (Fig. 6(b)), while the corresponding simulated temperatures are 1407.9 and 1051.6°C, and 1354.7 and 1124.3°C. The experimental results show that the corresponding positions of the two weldments cool through the sensitization temperature range (500–960°C) in approximately 26.2 (i.e. (78.7–52.5)) and 26.3 s, and 35.8 (i.e. (87.2–51.4)) and 37.4 s, respectively. Similarly, the simulation results show that the corresponding positions of the two weldments cool through the sensitization range in 27.5 (i.e. (79.8–52.3)) and 28.4 s, and 37.0 (i.e. (91.4–53.4)) and 37.1 s. Thus, the cooling rates are 16.7 and 16.2°C/s, and 12.4 and 12.4°C/s. From inspection, the simulation results for the weldment temperature and cooling rates are found to deviate from the experimental results by less than 5%.

The maximum experimental temperature at measurement positions \( T_{G13} \) and \( T_{G14} \) (Fig. 6(a)), and \( T_{G23} \) and \( T_{G24} \) (Fig. 6(b)), located in the WDZ region of the weldments, are 819.3 and 640.3°C, and 889.1 and 703.2°C, respectively, while the corresponding simulation values are 789.0 and 622.1°C, and 885.8 and 725.7°C. According to the experimental results, the corresponding regions of the two weldments cool through the sensitization range in approximately 29.6 (i.e. (72.4–42.8)) and 13.7 s, and 48.5 (i.e. (85.2–36.7)) and 27.3 s. The equivalent simulation values are 30.6 (i.e. (75.3–44.7)) and 21.9 s, and 46.0 (i.e. (86.0–40.0)) and 40.7 s,
respectively. Consequently, the basic validity of the numerical model is confirmed. However, it is observed that the experimental and simulated thermal cycles converge in the BM region of the two weldments, i.e., measurement positions TG15, TG16, and TG17; and TG25, TG26, and TG27. Note that the thermal cycles at these measurement positions are not discussed here.

4.4 Comparison of peak temperatures in different regions of weldment

Figures 7(a) and (b) present the numerical and experimental results for the peak temperature profiles in the 1st and 2nd pass GTAW weldments, respectively. Note that in both figures, the simulated temperature data are computed using the temperature-dependent values of the thermal properties given in Table 4. In performing the 1st welding pass, a higher power is required to penetrate the AISI 304 base metal, and the welding process is performed at a faster speed (150 mm/min, see Table 3). However, in performing the 2nd welding pass, sufficient time is required for the filler metal to form a weld bead, and thus the welding process is performed at a slower speed (90 mm/min). Consequently, the 2nd pass GTAW weldment receives a slightly higher heat input (1200 J/mm) than the 1st pass weldment (1120 J/mm). As a result, the temperature profiles in the 2nd pass GTAW weldment (Fig. 7(b)) have a smaller gradient than those in the 1st pass GTAW weldment (Fig. 7(a)).

In Figs. 7(a) and (b), the curves annotated “k=C” show the simulation results obtained when computing the temperature field within the weldment using constant values of the physical properties (derived at room temperature, 20°C) rather than the temperature-dependent values given in Table 4. In other words, the two curves represent a linear, rather than non-linear, treatment of the temperature field. It is observed that for both weldments, the temperature profile deviates more notably from the experimental profile than that calculated using the temperature-dependent values of the physical properties. This deviation confirms the importance of taking the temperature-dependent nature of the physical properties into account when simulating the welding process.

4.5 Calculation of time spent in sensitization region of weldments

As discussed in Section 4.1, Alloy 690 is prone to a sensitization effect at temperatures in the range of 620–1020°C. The amount of carbide phase precipitated within the HAZ of the weldment, and thus the susceptibility of
the weldment to IGC, depends on the time for which the weldment remains within this temperature range during the heating and cooling stages of the welding process. Accordingly, simulations were performed to investigate the temperature profiles at positions $T_{\text{GIA}}, T_{\text{GIB}}, T_{\text{GIB}},$ and $T_{\text{GIC}}$ (see inset in Fig. 8), respectively, such that the time for which each measurement position remained within the sensitization range could be calculated directly. (Note that the measurement positions outside of the sensitization region (e.g. the BM of the weldment) were not considered in the simulations.)

Figure 8 presents the simulated thermal histories, at each of the considered measurement positions. The durations for which the 1st pass GTAW weldment is heating and cooling through the sensitization range are approximately 32.8 s at $T_{\text{GIA}}, 25.2$ s at $T_{\text{GIB}},$ and 34.2 s at $T_{\text{GIC}}$. In other words, the weldment remains within the sensitization temperature range for a relatively short period, and thus IGC does not occur. Consequently, the etched weldment surface has a step structure, as shown in Fig. 4(a). The durations for which the 2nd pass GTAW weldment is heating and cooling through the sensitization range are approximately 80.8 (32.8 for 1st
pass + 48.0 for 2nd pass) seconds at $T_{G2a}$ and 67.2 (25.2 for 1st pass + 42.0 for 2nd pass) seconds at $T_{G2b}$. Thus, 2nd pass the weldment spends relatively more time within the sensitization temperature range than the 1st pass weldment, and is prone to IGC as a result. Consequently, the etched weldment surface has a ditch structure, as shown in Fig. 4(b).

5. Conclusions

This study has performed an experimental and numerical investigation into the temperature field induced within 1st pass and 2nd pass GTAW AISI 304 weldments in order to understand their respective sensitization tendencies. The validity of the numerical model has been confirmed by comparing the simulation results with the corresponding experimental results. The major findings of this study can be summarized as follows:

1. Oxalic acid etch test results have shown that the region of the HAZ in the 2nd pass of the GTAW AISI 304 weldment is susceptible to IGC and it is also found that the range of the peak temperature of the sensitization is between 500 and 960°C. In contrast, there was no evidence of IGC in the 1st pass weldment. The total heating and cooling duration of the HAZ of the 1st pass weldment is 34.2 s, after which there is no evident IGC ditch structure. In the 2nd pass weldment, however the...
The total heating and cooling duration is 67.2(25.2+42) s, and a ditch structure (indicating IGC) is quite evident.

2) Better agreement is obtained between the simulated temperature fields and the experimental temperature fields when the simulations take the temperature-dependent nature of the physical properties of the AISI 304 weldment into account.

3) The simulated transient temperature fields provide a reliable and convenient means of estimating the range and size of the sensitization zone following welding, and therefore should facilitate the subsequent alteration/repair of the IGC-affected weldment using LSM or LSP methods.

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Fig. 8 Simulated thermal histories at different measurement positions within sensitization region of 1st and 2nd pass GTAW weldments.