Effect of Surface Convection on Stationary GTA Weld Zone Temperatures

Weld pool surface temperature differences are related to different surface flow patterns

BY W. H. GIEDT, X.-C. WEI, AND S.-R. WEI

ABSTRACT. Weld pool surface temperature variations during cooling of stationary GTA welds in Types 303S and 304 stainless steel were measured with a narrow band infrared radiation pyrometer. Extrapolations of the pyrometer responses indicated peak temperatures at the end of a 3.5 second heating time of around 2000°C (3632°F) at the weld pool center for Type 304 stainless steel, but only around 1750°C (3182°F) for the Type 303S.

The fusion zone joint penetration of 4.06 mm (0.16 in.) in the Type 303S stainless steel was almost twice the joint penetration (2.30 mm/0.09 in.) in the Type 304 stainless steel. These differences appear to be primarily attributable to different surface flow patterns.

Measured results are also compared with predictions of the transient temperature variations made with a two-dimensional finite difference computer program.

Introduction

Since bonding of materials during welding occurs in the fusion zone, a minimum specified fusion zone penetration into the joint is required to provide a desired weld strength. For some time, however, it has been known that welding conditions, which produced welds of acceptable penetration in materials from one heat, may not produce sufficient joint penetration when material from a new heat is used (Ref. 1). These anomalous results have been shown to be attributable to variations in the concentration of minor alloying elements.

The mechanism (or possibly just one of the mechanisms) responsible has been revealed in a recent series of experiments conducted by Heiple and Roper on the effect of minor alloying elements on fusion zone shapes during GTA welding of 21-6-9 steel (Refs. 2, 3). Photographic observations of the movement of aluminum oxide particles on the molten surface revealed that the flow was normally from the center toward the perimeter of the weld pool. However, relatively small additions of surface-active constituents such as sulfur or selenium caused the flow pattern to reverse, i.e., the particles were seen to flow from the sides to the center of the weld pool. Furthermore, the pool narrowed and the joint penetration was found to increase by as much as 50 to 100%.

The explanation proposed for these rather dramatic changes was that the addition of surface-active elements caused the surface tension variation of the molten metal to change from a normally decreasing trend with increasing temperature to an increasing trend with increasing temperature. The result was that the surface tension driven flow or Marangoni convection caused a strong inward and downward flow.

An analytical investigation of the role of convection in weld pools was recently reported by Oreper, Eagar, and Szekely (Ref. 4). Using measured stationary GTA fusion zone profiles for the location of the liquid-solid weld interface, they solved for the steady-state flow and temperature fields. Buoyancy, electromagnetic, and surface tension forces were included. Their results showed that surface tension forces were dominant in many instances and indicated that higher central surface temperatures would occur when the flow was inward. This trend, however, was based on a fixed fusion zone geometry and hence would not account for the effect of a change in joint penetration.

The objective of the present investigation was to measure the surface temperature variations of weld pools in materials with different surface tension characteristics, and to determine if such measurements provide an indication of different surface flow patterns. Stationary GTA arc welding on essentially adiabatic disk-shaped specimens was selected to reduce system complexity. Since direct observations through an arc are difficult to interpret, it was decided to make transient measurements immediately after the arc had been terminated.

Tests were initiated with disk-shaped specimens of Type 304 stainless steel. These were followed with measurements using Type 303S stainless steel for which thermal properties are similar to those of Type 304 stainless steel, but the surface tension variation with the temperature of the molten pool was expected to be substantially different than that of Type 304 stainless steel. A numerical analysis was also developed based on a conduction model. Although good agreement between predictions from this model and the Type 304 stainless steel measurements was achieved, comparison with the Type 303S stainless steel measurements demonstrated the limitations of a pure conduction model.

Experimental Apparatus

Stationary gas-tungsten-arc (GTA) welds were made at the center of 3.0 in. (76.2 mm) diameter specimens with a commercial GTA AC/DC 300 ampere (A) welding unit.1 The electrode holder was mounted in two adjustable jaws in an

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1"Model TIG-300/300 AC/DC Arc Welder" manufactured by Lincoln Electric Co., Cleveland, Ohio.
Radiation from the emitting weld pool surface is focused by the optics of the infrared radiation-sensing probe onto the end of a fiber optic bundle. The target spot size is specified by the manufacturer to be 0.04 in. (1.0 mm) in diameter with a 15 in. (381 mm) focal length. The radiation is then transmitted through the fiber optic cable into an infrared detector head (photon counter). Here, the radiation is passed through a silicon filter to a lead sulfide cell where it is converted into an electrical signal. The detector has a radiation wavelength response band of approximately 1.0 to 2.5 μm (0.0001 in.). The manufacturer recommends treating instrument measurements as monochromatic at an effective wavelength \( \lambda = 1.526 \) μm (0.00006 in.). Variation of this effective wavelength with temperature is indicated to be negligible.

The signal from the detector is amplified and displayed as a direct current potential by the electronic digital console. The full-scale response time of the pyrometer is approximately 0.1 second(s). The DC output potential was recorded with a light-beam galvanometer type oscillograph. The radiant temperature (blackbody temperature) was then determined from a calibration curve obtained with a blackbody source. Assuming the spectral emittance of the specimen is known, the surface temperature can then be calculated as noted under "Surface Temperatures from Pyrometer Output."

It was not possible to observe the peak surface temperature due to the 0.1 s response time of the pyrometer. Consequently, tests were also conducted with AWG no. 40 platinum-platinum 13% rhodium and tungsten 5% rhenium-tungsten 26% rhenium thermocouples. These were mounted in 0.062 in. (1.58 mm) ceramic tubes and placed in holes drilled to within about 0.020 in. (0.508 mm) from the top surface of the specimens, directly under the location of the tungsten electrode.

Unfortunately, most of these thermocouples failed soon after the temperature reached the melting point. In the case of the Type 303S stainless steel, however, some initial pyrometer responses were exceptionally fast and higher in magnitude. Observation of the test specimens after testing indicated that the ceramic tubes had been exposed. This was caused by a depression in the center of the weld pool just above the thermocouple. This depression was evident in the upper surface of the solidified weld pools of Type 303S stainless steel specimens, and was apparently caused by downward flow of the molten metal in the central region of the weld.

Experimental Procedure and Representative Measurements

It was impossible to make all the mea-

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1Vanzetti Systems, model 1262.
2Brush Instrument Company, model 16-2308.
measurements desired during a single weld. For this reason, welds were assumed repeatable, and data were obtained during several tests. Every effort was made to provide identical energy inputs and flux distributions to each of the specimens by using identical welding conditions. All tests were conducted with the welding unit operating in the DC mode.

After several exploratory tests, a 200 A, 3.5 s time duration GTA spot weld on a 3 in. (76.2 mm) diameter and 3/8 in. (4.76 mm) thick Type 304 or 303S stainless steel specimen was chosen for the final experiments. The same electrode material and shape were maintained—namely, a 3.2 mm (0.126 in.) diameter thoriated tungsten electrode with a tip machined to a slender, sharp point (about 30 deg). The shape of the tip was checked before and after each run. The initial gap between the tungsten electrode and the specimen was carefully adjusted to be 1.0 mm (0.04 in.) for each test. The argon shielding gas flow rate was 35 cfm (16.5 L/min.) with 10 s pre- and postweld purges.

The welding electrode and round plate specimens were placed in a 80 mm (3.15 in.) diameter and 100 mm (3.93 in.) high stainless steel cylindrical chamber which was filled with argon to shield the weld pool surface from oxidation during welding and during cooling after the arc was turned off. The welding unit current control was set to 200 A for all tests. Measurements of the current and voltage across the arc yielded 200.2 A and 17 ± 0.3 volts (V), respectively.

Temperature histories for five Type 304 stainless steel specimens were recorded at five different radial locations, i.e., 0, 0.1, 0.2, 0.3, 4 mm (0, 0.04, 0.08, 0.12 and 0.16 in.) from the weld centerline. Because of the narrower and deeper fusion zone of Type 303S stainless steel, temperature histories were recorded at only three different radial locations, i.e., 0, 1, 2 mm (0, 0.04 and 0.08 in.) from the weld centerline.

Tracings of oscillograph records of representative optical pyrometer responses for Types 304 and 303S stainless steel are shown in Fig. 3. The Type 304 stainless steel record is typical of the cooling of molten metal with solidification and then cooling of the solid. The occurrence of solidification is clearly evident for Type 304 where the temperature is almost constant for about 0.5 s.

In contrast, the curve for Type 303S stainless steel suggests that the temperature did not rise much above the melting temperature. The nearly horizontal portion of the curve is interpreted as the solidification period. The second peak of the curve is attributed to oxidation of the material which has just solidified. Quantitative interpretation of these records will be discussed in the following sections.

Cross sections of the weld regions in both stainless steels are shown in Fig. 4. The fusion zone in the Type 304 is relatively wide and shallow, while that in the Type 303S is narrower and about 100% deeper. Also, there is a slight rise at the center of the Type 304 stainless steel specimen, but a small depression at the center of the Type 303S stainless steel specimen. The different flow patterns proposed by Heiple and Roper (Ref. 3) shown in Fig. 5 provide a very logical explanation for the results presented in Figs. 3 and 4.

Interpretation of Experimental Data

Surface Temperatures from Pyrometer Output

The pyrometer output is proportional to the energy flux at an effective wavelength of 1.526 μm (0.00006 in.) from a circular spot approximately 0.04 inch (1.0 mm) in diameter. The spectral intensity can be assumed to be equal to the blackbody spectral intensity B, multiplied by a spectral emissivity \( e_s \), determined from the pyrometer DC potential, is determined from the pyrometer calibration curve. This temperature is referred to as the radiant temperature \( T_r \).

Equating the energy flux from the actual surface to that from a black surface at \( T_b \) and solving for \( T_r \) yields:

\[
T_r = \frac{1}{[\alpha/(C_2)] \ln e_s + 1/T_b}
\]

where \( C_2 \) is the second Planck constant \((1.4387 \times 10^{-8} \text{ μm K})\). All of the quantities in this equation are known except \( e_s \).

Since no data for \( e_s \) were available, applicable values were determined from the experimental curves and additional measurements. At the almost horizontal region of a typical cooling curve (Fig. 3), the surface temperature is known to decrease from the liquidus to the solidus temperature. The mean radiant temperature \( T_r \) during this change can be determined from the pyrometer output record and the pyrometer calibration curve.

Using equation (1), the spectral emittance was calculated by substituting a
melting temperature \( T_M \) equal to the average of the solidus and liquidus temperatures, \( (T_{so} + T_{li})/2 \), for \( T_v \) the mean radiant temperature \( T_v \) described above and the effective 1.526 \( \mu \)m wave length for \( \lambda \). This yielded a value of \( \varepsilon_v = 0.39 \), which agrees with the value obtained by Shintaku et al. (Ref. 5) for Type 304 stainless steel in an electron beam welding chamber.

Test specimens were covered with a cylindrical chamber (Fig. 1) which was filled with the argon normally supplied by the welding unit for gas tungsten arc shielding. This procedure apparently inhibited surface oxidation up until the time solidification occurred. However, postweld examination of the surfaces indicated some oxidation of both types of specimens. Measurements of the normal spectral emittances with a spectrophotometer yielded values of around 0.7.

Accounting for Pyrometer Time Response

Sudden exposure of the pyrometer sensing element to the center of the molten weld pool resulted in the pyrometer output rising in about 0.1 s to an indicated maximum temperature of around 1560°C (2840°F) — Fig. 3. During this time period, the surface rapidly cooled from its maximum value to the value of about 1560°C (2840°F). In the next 0.1 s period, the pyrometer output decreased about 100°C (180°F) and during solidification the rate of decrease was around 50°C (90°F) in about 0.2 s intervals. These changes were small compared to the initial rise during the first 0.1 s; hence, after this the pyrometer measurements were considered to be close to the actual surface temperature variation. This was also true after solidification since the rate of change was then much slower.

To estimate the surface temperature variation during initial rapid cooling, the pyrometer response was investigated by exposing it to several step changes over the output range occurring in the experimental measurements. The output was found to be essentially exponential and could be described with a single average time constant of \( \tau = 0.09 \) s. The reason for this relatively simple result is hypothesized to be due to the fact that the primary factor controlling the transient behavior of the pyrometer was the amplifier response. The delay introduced by the radiation detector is apparently negligible in comparison. The actual surface temperature variation was then estimated with the above value of \( \tau \) using time steps of 0.025 s. Details are given in Ref. 6.
energy storage in terms of enthalpy. The effect of convection was approximated by specifying the thermal conductivity of the molten liquid to be several times the value of the solid at its melting temperature. Although this is not an accurate representation of convective effects, it reduces the problem to heat transfer by conduction only, and the transient fusion zone profile can be determined from the calculated temperature distributions. This is in contrast to the analysis described by Oreper et al. (Ref. 4) who specified the fusion zone as a boundary condition.

The 3.0 in. (76.2 mm) diameter and \( \frac{3}{4} \) in. (4.76 mm) thick specimens were divided into 288 volume elements, each with 0.031 in. (0.794 mm) radial and depth dimensions. An implicit solution technique was used with a time step of 0.05 s. Radiation heat loss from the upper surface was specified; the other surfaces were taken to be adiabatic. Additional details and a listing of the program are given by Wei (Ref. 6).

**Results and Discussion**

Interpretations of the experimental records from the Type 304 stainless steel tests, as described previously, are presented in Figs. 6–10; numerically predicted temperature variations are also included.

**Comparison of Predicted and Experimental Results for Type 304 Stainless Steel**

Computer program calculations were made for a series of values of:

1. Arc efficiency \( \eta \).
2. Radius of the heated region \( r \).
3. The effective thermal conductivity \( k_1 \) of the liquid.

Specimen thermal properties selected from the literature (Refs. 7, 8) are listed below:

\[
\begin{align*}
\rho &= \text{density} = 493.1 \text{ (lb/ft}^3) \\
k_s &= \text{thermal conductivity of solid} \\
&= 8.4 + 0.0038 (T - T_0) \quad \text{(Btu/h-ft°F)} \\
k_l &= \text{thermal conductivity of liquid} \quad \text{(KR)k}_s \\
T_{\text{Sol}} &= \text{solidus temperature} \\
&= 1400°C (2552°F) \\
t_{\text{l}} &= \text{liquidus temperature} \\
&= 1455°C (2651°F)
\end{align*}
\]

\( k_1/k_2 \) = Ratio of Liquid to Solid Thermal Conductivity

Fig. 6—Experimental and predicted surface temperature variations at center of stationary GTA weld in Type 304 stainless steel during cooling

Fig. 7—Experimental and predicted surface temperature variations 1.0 mm from center of stationary GTA weld in Type 304 stainless steel during cooling

Fig. 8—Experimental and predicted surface temperature variations 2.0 mm from center of stationary GTA weld in Type 304 stainless steel during cooling

Fig. 9—Experimental and predicted surface temperature variations 3.0 mm from center of stationary GTA weld in Type 304 stainless steel during cooling
Selection of applicable values for the arc efficiency $\eta$, the heated region radius $\bar{r}$, and the effective thermal conductivity of the liquid $k_l = (KR)k_s$ was based on obtaining agreement between the experimental and predicted width and depth of the fusion zone. Results showed that the arc efficiency and the heated region radius had stronger effects on the depth of the fusion zone than did the effective liquid thermal conductivity. However, $k_l$ did significantly influence the maximum surface temperature. Since the maximum heat flux (see equation (2)) varies inversely with $\bar{r}$, the fusion depth decreased rapidly with increasing $\bar{r}$, while the width decreased less rapidly. Although surface temperature distributions were also lowered, they were less sensitive to increasing $\bar{r}$ than was the maximum fusion depth.

Observation of results lead to the selection of $\bar{r} = 5.9$ mm to achieve matching of the experimental fusion zone width. This location coincided with the radius of the discolored area on the heated surface outside the fusion region. With this value for $\bar{r}$, good agreement between the predicted and the experimental fusion zone profiles was achieved with $\eta = 40\%$ and $KR = 3.5$ as shown in Fig. 11. The differences near the outer edge and near the bottom are due to the inadequate modeling of the effect of convective heat transfer. A value of 40% for $\eta$ is noted to be in the upper part of the range of values for GTA welding reported by Christensen et al. (Ref. 11) for an arc power of around 3.4 kW.

Predicted temperature variations at the weld pool center for values of the conductivity ratio $KR$ equal to 2.5, 3.0, 3.5, 4.0, and an arc efficiency of 40 percent are presented in Fig. 6. As can be noted, the main effect of changing $KR$ is on the peak surface temperature reached at the end of the welding period. This value decreases from about 2150 to 1880°C (3902 to 3416°F) as $KR$ increases from 2.5 to 4.0.

The best agreement between measured and predicted fusion zone widths (Fig. 11) was obtained with $KR = 3.5$. This value is consistent with values found by other investigators (Ref. 9), and it yielded a predicted peak surface temperature of 1950°C (3542°F), which is within 50°C (90°F) of the value of 2000°C (3632°F) estimated from the pyrometer response. Changing $KR$ did not have a large effect on the predicted fusion zone geometry. Note that good agreement between the experimental and the predicted values at locations of 1.0, 2.0, 3.0, and 4.0 mm (0.04, 0.08, 0.12, and 0.16 in.) from the center (see Figs. 7-10) was also achieved with $KR = 3.5$. The differences are within 5%.

Two of the thermocouples mounted in the weld specimens under the surface provided measurements up to the end of the arc heating period and indicated peak temperatures around 1750°C (3182°F). The junctions were located about 0.8 mm (0.03 in.) below the heated surface. A linear estimate of the surface temperature based on the melting temperature at the penetration depth of 2.4 mm (0.09 in.) yielded a value of 1900°C (3452°F). Recognizing that the effective location of the thermocouple junction is not very precise, this value is considered to add support to the estimated peak value of around 2000°C (3632°F).

Surface Temperature Results for Type 303S

Interpretations of the Type 303S stainless steel experimental records are shown in Figs. 12–14. The experimental results
for Type 304 stainless steel are also included for comparison.

As indicated in Fig. 12, the temperature of Type 303 stainless steel did not rise much above the melting temperature. This means that the molten pool surface temperature distributions should be different for Type 303S compared to Type 304 stainless steel welds.

Figure 4 shows the sharp contrast between the weld fusion zones in Types 303S and 304 stainless steel. The approximately 100% greater joint penetration in Type 303S stainless steel indicated that the flow of molten metal was inward rather than outward as suggested in Fig. 5. This difference in flow direction is attributed to the relatively high concentration of the surface active element sulfur in Type 303S stainless steel — Table 1.

Extrapolation of the experimental curve (as described in a previous section) for Type 303S stainless steel in Fig. 12 indicated that the peak surface temperature at the weld pool center was around 1700-1750°C (3092-3182°F); this was about 250°C (450°F) lower than that for the Type 304 stainless steel welds.

The extrapolated peak surface temperature was verified indirectly by measurements with AWG no. 40 platinum-platinum 13% rhodium thermocouples mounted in 0.062 in. (1.57 mm) diameter ceramic tubes and installed in the specimens about 0.030 in. (0.762 mm) from the top surface right under the weld pool center. Linear extrapolation of the measured peak temperature of 1550°C (2882°F) from the melting temperature at the maximum penetration depth of 4.0 mm (0.16 in.) yielded a surface temperature of 1650°C (3002°F), which is in reasonable agreement with the value of 1750°C.

In view of the lower peak surface temperature for Type 303S stainless steel, calculations with the computer program were made with higher values of the conductivity ratio KR as suggested by the trend of the results shown in Fig. 6A. With values of KR = 6, η = 40%, and τ = 5.9 mm or 0.23 in. (this was the radius of the discolored region which was about the same as for the Type 304 stainless steel specimens), the predicted peak surface temperature was approximately 1750°C (3182°F).

Although this is in satisfactory agreement with the measurements, the predicted fusion zone was not in good agreement with the experimental. The maximum width predicted at the surface was about 9.2 mm (0.36 in.). This is 15% greater than the 8.0 mm (0.31 in.) shown in Fig. 4. The disagreement in penetration depth was even greater. The measured value was about 4.0 mm (0.16 in.), which is 60% greater than the predicted. This indicates that the use of a fictitiously high liquid thermal conductivity does not account properly for convection in the weld zone of Type 303S stainless steel.

In several cases when thermocouples were installed in the Type 303S stainless steel specimens, a very rapid initial pyrometer response occurred (i.e., a rise to a maximum of 1700°C (3092°F) in about 0.05 s). Postweld inspection of these specimens revealed that a central depression had developed and indicated that the top of the ceramic tube had been exposed to direct heating of the welding arc. This could have been caused by a central flow as described above — Fig. 5. This result also adds strong support to the surface tension mechanism proposed by Heiple and Roper (Ref. 3).

Conclusion: Comparison With Other Results

The measurements described in this paper indicate that surface convection has an effect on weld pool surface temperature distribution. It is recognized, however, that the results presented are for relatively large differences in the sulfur concentration. A point of particular interest is whether the central region temperatures are higher, or lower when the surface flow changes from an outward to an inward direction.

As mentioned in the Introduction, higher central temperatures were predicted by Oreper et al. (Ref. 4) when the surface tension of the liquid increased with temperature. However, this could have been influenced by the assumption of a fixed liquid-solid boundary profile (i.e., possible change in penetration was not accounted for in their study).
for). Although the opposite trend was found in the present experiments, this may have been due to exceptionally strong surface convection. Additional measurements using a series of specimens with surface-active element concentrations varying in selected steps over the range of interest should be made. The possibility of improving pyrometer response should also be investigated.

The peak central temperature in Type 304 stainless steel indicated by the measurements was around 2000°C (3632°F). Based on absolute temperatures, this is approximately 1.3 times the melting temperature. Results presented by Oreper et al. (Ref. 10) showed central region isotherms of over 1.6 times the melting temperature for a carbon steel. Recent weld pool temperature measurements by Sundell et al. (Ref. 10), during bead-on-plate GTA welding in 1/4 in. (6.4 mm) thick carbon steel plates, using 0.010 in. (0.25 mm) tungsten–tungsten rhenium thermocouples, and located approximately 0.015 in. (0.38 mm) below the surface, indicated average peak central temperatures of around 3100°F (1700°C). Assuming the surface temperature to be about 150°C (270°F) higher, the ratio of the peak surface temperature to the melt temperature is about 1.2, this is consistent with present results. Thermocouple measurements in spot welds of approximately 8 s duration in Type 304 stainless steel were also presented by Sundell et al. (Ref. 10). The peak value recorded was 2700°F (1480°C). This is only about 25°C (45°F) above the liquidus temperature and appears to be low.

The effect of sulfur addition was also investigated in the study reported by Sundell et al. (Ref. 10). FeS2 powder was added in a small hole drilled in Type 304 stainless steel weld specimens. An oscillating thermocouple output was obtained with indicated peak temperatures of around 3000°F (1650°C). This is similar in magnitude to the results obtained in this study for Type 303S stainless steel.

Since inward surface fluid flow was observed in these tests, it is possible that the thermocouple probe introduced some disturbance and that conditions immediately above the ceramic support tube varied with time. Further study to investigate this hypothesis is recommended.

Acknowledgment

The assistance of the Lawrence Livermore National Laboratory in supplying the material for the SS-304 test specimens is gratefully acknowledged.

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PUBLISHED BY THE AMERICAN WELDING SOCIETY, P.O. BOX 351040, MIAMI, FL 33135

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