ABSTRACT. This paper describes a method of determining the optimal sensor location to measure weldment surface temperature, which has a close correlation with weld pool size in the gas metal arc (GMA) welding process. Due to the inherent complexity and nonlinearity in the GMA welding process, the relationship between the weldment surface temperature and the weld pool size varies with the point of measurement. This necessitates an optimal selection of the measurement point to minimize the process nonlinearity effect in estimating the weld pool size from the measured temperature. To determine the optimal sensor location on the top surface of the weldment, the correlation between the measured temperature and the weld pool size is analyzed. The analysis is done by calculating the correlation function, which is based upon an analytical temperature distribution model. To validate the optimal sensor location, a series of GMA bead-on-plate welds are performed on a medium-carbon steel under various welding conditions. A comparison study is given in detail based upon the simulation and experimental results.

Introduction

Arc welding is a process to fuse and join metal pieces using the electric arc generated from the flow of electric current through the electrode and the weldment. As with all fusion welding processes, arc welding involves melting and resolidification of the base material. Therefore, the geometry of the resulting weld bead is a good indicator of weld integrity. The geometry of the weld bead can be represented by the bead width, the root surface width and the depth of joint penetration. A successful weld is characterized by a relatively high depth-to-width ratio of the weld bead. Therefore, the geometry of the weld bead must be measured and controlled to ensure uniform weld quality.

One of the representative methods for measuring weld bead size is an image processing technique by which the weld bead geometry is measured by a CCD camera whose image data are processed to obtain the shapes and sizes (Ref. 1). However, there are some restrictions on the direct utilization of this technique in the gas metal arc welding (GMAW) process. The transfer of electrode melting droplets to the weldment causes spatter and the spreading of molten metal from the electrode onto the weld bead, degrading the image sensor's ability to measure the weld bead geometry. Another method, which compensates for the weaknesses in the image processing technique, is to measure a heat flow pattern in the weldment and derive from it the geometrical shape and size of the weld bead. To determine the heat flow pattern, Ramsey, et al. (Ref. 2), measured the radiation from the surface of the weldment by using fixed or scanning infrared radiometers. Lukens and Morris (Ref. 3) used cooling rates, which were monitored by measuring the temperature on the surface of the weldment, in order to monitor variations in material microstructure. There is a fundamental problem in estimating weld bead sizes from the measurement of the heat flow pattern in the weldment. The problem is due to the fact that the heat flow pattern in the weldment is estimated from the surface temperature measured by a finite sensor. It is, therefore, very important to obtain a relationship between the measured temperature and the weld bead size in order to estimate the weld bead size from the heat flow pattern measured at the finite points on the weldment. Because the temperature distribution in the weldment may vary in accordance with such welding conditions as travel speed and heat input, the relationship may change depending upon sensor location, as well as welding conditions. Ramsey, et al. (Ref. 2), and Lukens and Morris (Ref. 3) selected a point of maximum temperature on the upper surface of the weldment as the sensor location. Kozono, et al. (Refs. 4, 5), selected the point of maximum temperature on the weld line of the weldment as the sensor location. The choice of this point as a measurement location was based on the fact that the variation of the measured temperature with sensor location is minimized here. However, because these measurement points were determined for specific welding conditions, the optimal sensor location for a given welding process must be determined.
conditions at a quasi-stationary state, the above methods suffer because the relationship between the measured temperature and weld bead size varies in accordance with variations in welding conditions.

In this paper, a method is presented to determine an optimal measurement location that will minimize the effects of process variations on the estimation of weld bead sizes from measured temperatures. A cross-correlation between the surface temperature and the weld pool size is analyzed to determine the optimal sensor location on the surface of the weldment. The optimal sensor location is determined so that the correlation coefficient is maximized.

**Heat Flow in the Weldment**

In order to obtain the analytical correlation between the measured temperature and the weld pool size, a mathematical model is required to calculate the temperature field in the weldment. In other words, a heat flow analysis is needed to understand the formation of the weld bead and to study the effect of various welding conditions, such as heat input and travel speed, on the temperature distribution in the weldment.

Since the welding process causes very complex physical and metallurgical changes in the workpiece, it is practically impossible to establish an exact mathematical welding model. In particular, the temperature-dependent characteristics of the physical parameters of the weldment make the problem more intractable. Various other physical phenomena in the welding process, such as phase change and heat convection due to forced flow of the molten pool, further increase the difficulty of the mathematical analysis. Rosental (Ref. 6) was the first to reduce the problem to manageable size by assuming temperature invariant characteristics of the physical parameters. He derived the temperature distribution equations for point, line and plane heat sources by utilizing the conventional heat conduction model for the quasi-stationary state. These mathematical formulations qualitatively revealed the effects of the welding parameters on the weld pool shape. Nevertheless, many researchers have shown that this solution leads to large errors in predicting temperature distributions because it is based on too many assumptions. Recently, Boo and Cho (Ref. 7) derived a new analysis of the temperature distribution of the process under more realistic assumptions. Their analytical model describes the three-dimensional temperature fields in a finite thickness plate heated by a source of Gaussian distribution moving along the welding line. To account for the flow of the shielding gas, a forced convection boundary condition is assumed at the top surface of the weldment and a natural convection condition is assumed at the bottom surface. This model can provide more accurate prediction of the joint penetration depth for a finite thickness weldment and the root surface width for the case of root pass welding (Ref. 7).

The coordinate system in this analysis of the weldment and the traveling welding gun is shown in Fig. 1. In this figure, X, Y, and Z denote the coordinate system fixed at the origin of a world coordinate, a point on the surface of the weldment, while x, y, and z denote the moving coordinate system, with origin fixed at the arc center (Xa, Ya, 0). The resulting solution for the temperature distribution in the moving coordinates (x, y, z) at time t, due to the applied heat input, is expressed by the following equation:

\[
T(x, y, z, t) - T_0 = \int_0^1 \frac{q(t)}{2\pi r_0 \rho c d} \times \frac{1}{\sigma^2 + a(t-t_0)} \times \exp \left\{ \frac{(x + X_a(t) - X_a(t_0))^2 + (y + Y_a(t) - Y_a(t_0))^2}{2\sigma^2 + 4a(t-t_0)} \right\} \sum_{n=0}^\infty A_n \exp \left( -\mu_n^2(t-t_0) \right) \left( \cos \left( \frac{\mu_n x}{\sqrt{\alpha}} \right) + \frac{\beta_n \sqrt{\alpha}}{\mu_n} \sin \left( \frac{\mu_n y}{\sqrt{\alpha}} \right) \right) \sin \left( \frac{\mu_n z}{\sqrt{\alpha}} \right) \, dt_1
\]

where \( T(x, y, z, t) \) is the temperature at a point (x, y, z) in the weldment at time t, and \( \alpha = k/pc \) is the thermal diffusivity, in which p, c, and k are the density, specific heat and thermal conductivity of the weldment, respectively. \( \mu_n \) is the positive eigenvalue satisfying the following equation:

\[
\tan \left( \frac{\mu_n \sqrt{\alpha}}{\sqrt{\alpha}} \right) = \frac{2\sqrt{\alpha \mu_n (\beta_1 + \beta_2)}}{\mu_n - \beta_2 \alpha}
\]

where \( \beta_1 = h_1/k \) and \( \beta_2 = h_2/k \), in which \( h_1 \) and \( h_2 \) are the effective convection coefficients at the top surface and the bottom surface, respectively, and \( A_n \) is defined as

\[
A_n = \frac{\mu_n^2 d}{\mu_n^2 d + \alpha \beta_2 d + 2 \alpha \beta_1}
\]

The distribution of the arc, \( Q(x, y, t) \), is assumed to take the form of a Gaussian function and is given by

\[
Q(x, y, t) = \frac{q(t)}{2\pi \sigma^2} \exp \left( -\frac{(x^2 + y^2)}{2\sigma^2} \right)
\]

where \( \sigma \) is the distribution parameter, which has dimensions of length and can be considered as the half-width of the arc, \( q(t) = \eta V(t) \) where \( \eta \) is the arc efficiency, and \( V(t) \) is the electric power input. The temperature of a point (x, y, z) in the weldment at time t can be found by solving for the heat input history \( V(t) \). The weld bead size can also be obtained by searching for the constant temperature contour whose value is equal to the melting point of the material.

To carry out an analytical study with
this model, it is necessary to obtain the parameters contained in Equation 1. These are cited in Ref. 7. The parameters listed in Table 1 are the physical properties of hot rolled AISI 1025 at 700°C (1292°F). The material properties vary slightly with temperature, but they are assumed here to be fixed at the 700°C values. These are approximately the average values over the range from room temperature (25°C; 77°F) to the melting temperature (1495°C; 2723°F).

The area directly beneath the nozzle of the welding gun experiences forced convection due to the flow of the shielding gas, while the other side of the weldment experiences natural convection. For these convection boundary conditions, the forced and natural convection heat transfer coefficients are obtained from the empirical relations used in Refs. 8, 9. The arc efficiency of GMA welding may vary depending upon the welding conditions and materials. Arc efficiencies of 60 to 80% were reported by Rykalin and Nikolaev (Ref. 8) for the direct current and direct polarity (DCDP) GMA welding of steel plates. A precise heat distribution factor, which determines the arc shape, is very difficult to obtain, since many factors influence the arc shape. Here, the ε value suggested in previous studies (Refs. 8, 9) is adopted.

Figure 2 illustrates variations of the weld bead sizes vs. power per unit length for various welding speeds. Experimental weld bead sizes are obtained by examining the microstructures of the weld sections, which are prepared by cutting and polishing the weldment after the welding is done. A weld pool boundary is obtained by measuring the dendrite area of the microstructure exposed by etching a sectioned weld with 3% Nital. These measurements are performed to obtain the unknown parameters ε and η required for the solution of Equation 1. Since previous studies only define the range of values within which ε is admitted to vary, the values of ε and η are varied within the recommended ranges to obtain a range of shapes for the weld pool. These calculated pool shapes are compared with those experimentally obtained. From this comparison, the parameters ε and η are chosen to yield the best fit between the calculated shapes and the experimental ones.

### Determination of the Optimal Sensing Location

Many researchers (Refs. 2–5) have measured the energy radiated from the surface of the weldment in order to monitor the weld bead geometrical parameters, such as bead width, depth of joint penetration and root surface width. Particularly in the case of the GMA welding process, the measurement of this radiation is considered a very effective method, as it avoids those difficulties inherent in the direct measurement of weld pool geometrical parameters arising from the melting electrode material spreading on the surface of the weldment. Because the temperature distribution in the weldment is governed by a partial differential heat conduction equation (so-called distributed parameter system), the distribution over the spatial extent of the weldment must be measured in order to obtain the weld bead geometrical para-

### Table 1 — Physical Properties of the Weldment

<table>
<thead>
<tr>
<th>Property</th>
<th>Notation (Unit)</th>
<th>Weldment (Mild Steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>$k (W/m \cdot ^\circ K)$</td>
<td>30.3</td>
</tr>
<tr>
<td>Specific heat</td>
<td>$c (J/kg \cdot ^\circ K)$</td>
<td>752</td>
</tr>
<tr>
<td>Density</td>
<td>$p (kg/m^3)$</td>
<td>7860</td>
</tr>
<tr>
<td>Forced convection heat coeff.</td>
<td>$h_f (W/m^2 \cdot ^\circ K)$</td>
<td>50</td>
</tr>
<tr>
<td>Natural convection heat coeff.</td>
<td>$h_n (W/m^2 \cdot ^\circ K)$</td>
<td>18</td>
</tr>
</tbody>
</table>

Fig. 2 — Bead width and joint penetration plus half the root surface width vs. power per unit length for various welding speeds: weldment thickness = 4 mm.
Correlation between Weld Bead Geometry and Sensor Location

The main objective for measuring the surface temperatures of the weldment is to estimate accurately variations of weld pool size during arc welding under various welding situations. As suggested by Fig. 1, the temperature sensor for measuring the radiation from the surface of the weldment can be located anywhere in the coordinate system whose origin is located at the arc center. However, the correlation between the weld pool geometrical parameters and the measured temperature at a given point may vary with sensing location. Thus, to monitor accurately the variation of weld pool size during arc welding, it is very important to select the sensor location for which the measured temperatures are most highly correlated with variations in weld pool size. To evaluate the correlation between the measured temperatures at a point and the weld bead sizes, the correlation coefficient is used and given by

$$\rho_{wT} = \frac{\sigma_{wT}}{\sigma_w \sigma_T} \quad -1 \leq \rho_{wT} \leq 1$$  \hspace{1cm} (5)

where \(w\) represents the weld pool geometrical parameters, such as bead width, depth of joint penetration, and root surface width, and \(T\) is the temperature measured at a point on the surface of the weldment. The \(\sigma_w, \sigma_T\) and \(\sigma_{wT}\) are, respectively, the variance of \(w\), the variance of \(T\), and the covariance of \(w\) and \(T\). They are defined by

$$\sigma_w^2 = E \left[ (w - \bar{w})^2 \right]$$  \hspace{1cm} (6)

$$\sigma_T^2 = E \left[ (T - \bar{T})^2 \right]$$

$$\sigma_{wT} = E \left[ (w - \bar{w})(T - \bar{T}) \right]$$  \hspace{1cm} (7)

where \(E[\cdot]\) denotes expectation value, and \(\bar{w}\) and \(\bar{T}\) are the mean values of \(w\) and \(T\), respectively. The magnitude of the correlation coefficient \(\rho_{wT}\) can be used to assess the degree of linear dependence between any two variables \(w\) and \(T\) on a scale from \(-1\) to \(+1\).

Simulation Study

Simulation Method

The main objective of the analysis of sensor location is to obtain the correlation coefficient given by Equation 5 for all possible sensing locations of the weldment and thus to determine an optimal sensing location. The calculation of the correlation coefficient between the temperatures and the weld pool sizes is examined in the context of the analytic solution of Equation 1. The geometrical parameters that represent the weld bead sizes are classified by two factors. One is the weld bead width; the other is the joint penetration depth plus half the root surface width. The joint penetration depth is a measure of weld integrity for the case of partial penetration welding. The half root surface width is the measure for the complete joint penetration welding.

The computer simulation is performed for both transient and quasi-stationary states. The objective for calculating the correlation coefficient at transient state is to obtain a relationship between the measured temperatures and the weld pool sizes as welding progresses. The distribution of the correlation coefficients over all measurement positions for the quasi-stationary state was also examined to find the variations in the relationships between the weld bead sizes after welding is done and the measured temperature at the quasi-steady state according to the measurement points. The welding parameters that affect the weld bead size in the arc welding process are heat input and welding speed for given materials having the same dimensions. In this study, however, an unified parameter, heat input per unit length, has been used to change the weld bead size and the temperature field in the weldment. It is defined by dividing the heat input by the welding speed. Heat input per unit length used in all simulations ranges from 700 to 1300 J/mm and the welding speeds are set at 4, 6, and 8 mm/s. At the transient state, the heat input per unit length ranges from 700 to 1300 J/mm and changes randomly every 10 s for 240 s.

Simulation Results and Discussions

Figures 3 and 4 show the correlation maps at the transient state and present the contour of the correlation coefficients as a function of measurement point on the surface of the weldment. The maps are obtained by connecting all points with the equi-correlation coefficient. In these
The positive direction along the horizon-

Thus, the origin is located at the arc cen-
ter in the direction of welding gun travel.

The solid lines represent the contours with the equi-correlation coefficient, and the values associated with the solid lines are the correlation coefficients of the contours. Figure 3 is a map of the correlation between the bead width and the measured temperature on the surface of the weldment. Figure 4 is a similar map for the case for the half root surface width plus the joint penetration depth as a weld bead geometrical parameter. It can be observed from Fig. 3 that when the measure-

Figure 5 is the map of the correlation coefficient for the case of bead width as a weld pool geometry factor in a quasi-stationary state. Figure 6 illustrates the case for the half root surface width plus penetration depth. The hatched area in Fig. 5 indicates the regions for which the correlation coefficient is higher than 0.95. If the temperature sensor is located at an inner point in this area, the weld bead sizes at a steady state must be very accurately estimated from the measured surface temperature. From the figure, it can be seen that the gradient of the correlation coefficient in the welding gun travel direction is very large, while the gradient in the opposite direction is very small. This shows a trend similar to that of Fig. 3. From careful study of Fig. 5, it can be noted that in the region of x < -10 mm and y >10 mm the correlation coefficient has contours parallel to the welding line. This is a major difference between the results at a quasi-stationary state and at a transient state. Figure 6 illustrates re-

The measured temperature will be highly correlated with the bead width. Thus, the variation of bead width can be accurately estimated from the measured temperature during arc welding. Figure 4 shows results similar to those illustrated in Fig. 3. In Fig. 4, the hatched area represents the region with maximum corre-

From the results shown in Figs. 3–6, it can be concluded that the optimal position of the temperature sensor must be located within the region of -12 mm < x < -10 mm and 3 mm < y < 7 mm, which is a superposition of the hatched areas. Therefore, both transient variations and steady-state values of the weld bead sizes can be accurately estimated during welding by monitoring the temperature at the proposed optimal position.

Experiments

Experiments were performed to com-

From careful study of the figure, it can be seen that the gradient of the correlation coefficient in the welding gun travel di-
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terline of the base metal, and Ar gas was used for shielding. The base metal was a hot rolled AISI 1025 steel plate, which had dimensions of 200 x 60 mm (7.8 x 2.4 in.) x 4 mm (0.16 in.) thick. The welding experiments were performed for every heat input per unit length of 100 J/mm from 700 J/mm to 1300 J/mm and for welding speeds of 4, 6 and 8 mm/s (9.5, 14.4, 18.9 in./min. The experiments were repeated three times for the same welding condition.

Comparison between Simulation and Experimental Results

Figure 7 shows the relationships between the geometrical parameter and the measured temperature for various measurement locations. From this figure, it is observed that the relationships vary with the change of the measurement locations and depend slightly upon the welding speed. From careful examination of the figure, it can be shown that the relationship obtained for a measurement location of (-14, 7, 0) exhibits much better linearity than those obtained for the other two cases.

Figure 8 is a comparison of the experimentally obtained correlation coefficients and the theoretically obtained ones for various measurement points. Figure 8A illustrates the variation of the correlation coefficient vs. distance along a line 7 mm (0.28 in.) away from the welding line (y = 7 mm), while Fig. 8B illustrates the variation of the correlation coefficient along the y axis perpendicular to the welding line with x fixed at -9 mm (-0.35 in.). It appears that the experimental results are in good agreement with the theoretical ones. In particular, the trend of the experimental results is very similar to that of the theory. However, in the case of the results for the joint penetration depth plus half root surface width, there appears to be a little discrepancy between the two. This difference is probably due to mathematical modeling error related to the inability of the model to describe exactly the nonlinearity of the welding process (e.g., convection effects in the weld pool, temperature-dependent variation of material properties, latent heat effect, etc.). It is well known that the shape of real weld pools depends on convection effects in the pool. However, the analytic solution includes heat conduction only, thereby providing the temperature distributions, which differ from the real phenomena. It can be observed from Fig. 2 that the bead width increases almost linearly with the heat input per unit length, while the penetration depth plus half root surface width increases nonlinearly. A nonlinear relationship is due to a steep variation of the weld pool near the fully penetrated state of the weld. Since the weldment under the surface exerts an insulating effect on heat flow through the thickness and, as a result, heat is retained in the metal, the increase in depth of penetration of the weld pool accelerates even with a slight increase in the heat input. From the results shown in Fig. 8A, it can be observed that in the case of bead width, the measurement point with maximum correlation coefficient is x = -14 mm and x = -12 mm for the case of penetration depth plus half root surface width. This is because the maximum temperature of the weldment occurs in the direction opposite to gun travel due to accumulation of heat, and the weld pool is formed in the region in which temperature reaches the melting point. The correlation coefficients decrease with an increase of distance along the welding axis because the weld pool is not generated in this region of the weldment. From examination of Fig. 8B, it can be
concluded that decreasing the distance away from the welding line results in a decrease of the correlation coefficients. From the careful comparison of the experimental results and theoretical ones, it can be concluded that the optimal measuring point to estimate the variation of the weld bead size formed at quasi-stationary states must be located on the region of $-14 \text{ mm} < x < -9 \text{ mm}$ and $0 < y < 8 \text{ mm}$.

**Conclusions**

A method has been presented for determining an optimal measurement point to estimate the variation of the weld pool size with the surface temperature during GMA welding. The correlation coefficient between measured temperature and weld pool size is taken as the criterion by which to determine the optimal measurement point.

From the results of the experiments and theoretical analysis obtained for various welding conditions, it can be concluded that the correlation significantly changes with the measurement location. The optimal measurement point has been determined to be a point which yields the maximum correlation value and must be located at the region of $-12 \text{ mm} < x < -10 \text{ mm}$ and $3 \text{ mm} < y < 7 \text{ mm}$ for the GMA welding of a mild steel. If the surface temperatures of the weldment are measured at the proposed optimal positions, both transient variations and steady-state values of the weld bead sizes can be accurately estimated during welding. Since the heat flow patterns vary in welding other materials, different measurement positions may be obtained as the optimal position on the basis of the proposed method.

**References**


