Use of Emission Spectroscopy for Welding Arc Analysis

The adaptation of emission spectroscopy methods to welding arc diagnostics is discussed with emphasis on dealing with the special problems encountered

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ABSTRACT. Various emission spectroscopy techniques which are applicable to gas tungsten welding arcs are discussed. Particular emphasis is placed on application under conditions experienced during actual welding operations such as arc fluctuations induced by the moving weld pool and limited observation time. With specialized instrumentation these problems can be overcome and useful determinations made of the heat flow geometry within the arc.

Introduction

The analysis of gas tungsten arc (GTA) welding processes is hampered by the difficulty encountered in measuring the pertinent characteristics of the arc. Total arc current and voltage are relatively easy to monitor, but changes in fusion zone geometry often occur without any detectable change in these parameters. A measure of the distribution of the heat flow from the arc to the weld pool, in addition to knowledge of total heat flow, is needed if shape as well as volume of the fusion zone is to be predicted.

The most suitable diagnostic technique for welding arc study is optical emission spectroscopy, because it does not disturb the arc and it allows measurement of arc parameters at discrete points. Spectroscopic techniques for determining temperature, electron density, and gas density (gas mixture) of plasmas are discussed in the literature (Ref. 1). The plasma of an atmospheric pressure argon arc encountered in a typical welding process is one of the simpler cases (the methods of equilibrium thermodynamics are applicable), and in 1959, H. N. Olsen (Ref. 2) treated such an arc in some detail. From measurements of temperature distributions, he calculated current distributions, electron densities, gas densities and other parameters of an arc between a tungsten electrode and a water cooled copper plate. The cooled copper plate (no molten pool) provided the long term arc stability needed to make measurements at multiple points in the arc.

The development work described here focused primarily on the problem of determining temperature and current distributions in an argon shielded arc during actual welding. Under such conditions, Olsen's methods were impracticable because the data collection required time spans which were much longer than a typical weld, and the data processing method assumes a pure argon plasma which is not generally obtained in an arc above a molten pool. In the latter case, the arc plasma may be considered to include three regions: pure argon plasma (near the tungsten electrode), metal vapor dominated plasma (immediately above the weld pool), and mixed argon and metal vapor plasma (in between).

In the following section, three measurement techniques are described which are particularly suited to each of these three regions. Also, the constraints pertinent to each of the three techniques are presented to help in selection of the appropriate technique for a given diagnostic need.

Measurement Techniques

Pure Argon Plasma Intensity—Maximum Method

Temperature measurements can be made using Olsen's method during a weld if the area of interest is the upper part of the arc (nearest the tungsten electrode), and the data acquisition rate can be greatly increased. Fortunately, the latter problem can be met using a recently developed instrument known as an Optical Multichannel Analyzer (OMA®*) which records intensity as a function of one dimension and stores that data digitally for later retrieval by various means including oscilloscope display or panel readout. With this device mounted in the proper orientation at the exit aperture of a monochrometer, the intensity of a single spectrum line can be measured at 500 points along the length of the entrance slit image in a time interval as short as 33 milliseconds.

By imaging the arc on the entrance slit with the arc axis perpendicular to the slit length, the line intensity as a function of position along any diameter of the arc can be collected and stored in digital format at a rate which is quite rapid compared to the gross fluctuations of the arc (~1 Hz). Using suitable interfacing, this digital information can be fed directly to a computer for calculation of radial temperature and current density distributions according to the same analysis as Olsen's (see Appendix A).

This system greatly facilitates studies in which a cooled copper anode is used, such as the analysis of electrode shapes and weld groove designs. Figures 1 and 2 illustrate the use of this system in comparing two electrode shapes. The half-width of the current density distribution was found to be a convenient parameter for evaluating

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potential welding behavior. Narrower half-width implies better weld penetration with other parameters held constant. The data were taken midway between the tungsten electrode and the copper anode rather than just above the anode. This was a consequence of the fact that the 100 ampere arc was not hot enough nearer the anode to yield an intensity maximum. If the region just above the copper anode is of interest, two intensity profiles must be recorded, one in the middle of the arc and the other at the anode surface. The intensities measured near the anode are then ratioed to the maximum intensity of the profile from the middle of the arc to calculate the desired temperatures.

As mentioned earlier, however, this method is only applicable to the upper portion of an actual welding arc. This is a result of the fact that there is a significant amount of metal vapor evolving from the weld pool surface and extending as far up as the midpoint of the arc when the metal contains significant quantities of high vapor pressure elements such as manganese. Since the proportions of the argon-metal vapor mixture are not known, the argon density cannot be determined for the calculation of line intensity as a function of temperature. Thus, some other method is needed to measure temperature in this argon-metal vapor mixture.

Mixed Argon-Metal Vapor—Plasma-Line Ratio Method

A common spectroscopic method for determining plasma temperatures when the density of the emitting atoms or ions is not known or cannot be calculated is the method of line intensity ratios. If the intensities of two emission lines of the same species are measured under identical conditions, the plasma temperature can be calculated from their ratio because the density factors (Eqn A1, Appendix A) cancel out. In order to have identical conditions, the measurements must be made (1) at approximately the same point in the plasma, (2) at the same sensitivity, (3) and in the case of a fluctuating arc, at the same point in time, and (4) the two lines must have excitation potentials (Appendix A) which differ by an amount on the order of the plasma temperature (expressed in electron volts). In the work discussed here, the first two conditions are met by using two lines which are near enough in wavelength to be observed at the exit aperture of the monochrometer simultaneously (without changing the grating angle). The OMA® can be used to meet the third condition by mounting it on the monochrometer in the orientation for measuring intensity as a function of wavelength. This allows simultaneous measurement of the two line intensities at a single point in the arc.

The only argon atomic lines which meet the fourth condition are separated by approximately 2000 angstroms. In view of the other requirements, such lines can only be monitored by two monochrometers or a specially instrumented spectrograph; either of these alternatives is expensive and cumbersome. Argon ion lines, on the other hand, are more numerous and at least one suitable pair of lines is available (4579.35 and 4589.90 angstroms).

Using the ratio of the intensities of these two argon ion lines, temperature measurements can be made in the area of the arc containing metal vapor. However, the ion lines are only detectable in regions of the arc that are hot enough to ionize a significant fraction (~10%) of the argon gas. This condition limits ion line measurements to the plasma nearer the axis of the arc and somewhat above the weld pool surface. As a result, temperature distributions generally cannot be obtained over a sufficient range of radius to calculate the half-width.

As can be seen from Figs. 1 and 2, the arc with the highest temperatures near the arc axis does not necessarily have the smallest half-width, i.e., best

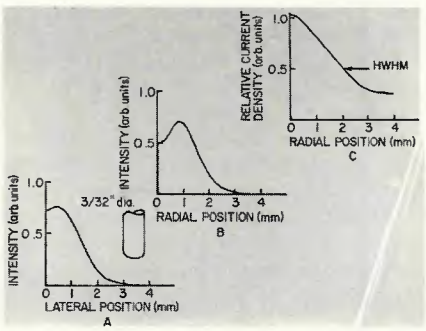

Fig. 1—Experimental intensity profile (7635.1 angstroms argon atomic line) and approximate electrode shape (A); Abel-inverted intensity distribution (B); relative radial current density distribution (C)

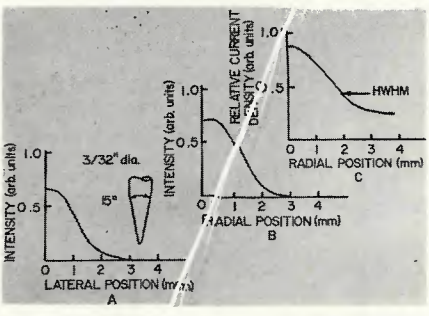

Fig. 2—Experimental intensity profile (7635.1 angstroms argon atomic line) and approximate electrode shape (A); Abel-inverted intensity distribution (B); relative radial current density distribution (C)

welding performance. However, this method does permit measurements of axial temperatures in this intermediate region which may be needed for more complete characterization of arc behavior. It should be noted that this method is useful in the pure argon plasma when temperature profiles are not required.

Metal Vapor Dominated Plasma

Reason suggests that characteristics of the arc immediately above the weld pool are most relevant to fusion zone geometry. However, the temperature gradients at the weld pool surface are such that some of the metal is vaporized, and the hydrostatic pressure of this vapor forces it up into the arc. The flow of shielding gas from the torch tends to hold the vapor near the pool surface. Here radiation cooling due to strong excitation of the metal vapor atoms (ionization potentials are ⅓ to ½ that of argon) lowers the temperature below the limit for argon ion line measurements. Therefore, spectroscopic measurements in the metal vapor-dominated region immediately above the weld pool must be based on the emission spectra of the elements present in the base metal.

In the work presented here, GTA welding of 304L and high manganese stainless steels was of primary interest, and the relatively high vapor pressure of manganese made it the predominant element in the metal vapor plasma.

Again, because the manganese (Mn) vapor pressure is not known as a function of temperature, the method of line intensity ratios is required for temperature measurements. Two manganese lines which meet all the restrictions discussed in the previous section occur at 5341.1 and 5377.6 angstroms. These two lines were selected because they are less susceptible to reabsorption than other, brighter lines of the Mn spectrum. Reabsorption (of light emitted from the hot center of the arc in the cooler periphery) is very strong for many lines of the metal spectra. The problem can be minimized by choosing lines which do not result from electron transitions to the ground or low-lying states of the atom.

Intensity profiles of the two manganese lines were recorded with a real-time data acquisition system developed for this work. An example of two profiles plus the temperature profile calculated from the intensity ratio at each point is shown in Fig. 3. Note that these profiles are not radial distributions like those shown in Figs. 1 and 2 because the inversion process described in Appendix A requires that the light emitting volume be circularly symmetrical. In general, the distribu-

tion of metal (Mn) vapor is not circularly symmetrical due to fluctuations of the pool surface and the gradients established by the motion of the arc along the base metal. Therefore, the Mn light emission is not circularly symmetrical even if the actual temperature distribution is very nearly so (Eqn A1, Appendix A).

In contrast to the case of a pure argon arc, the current density distribution cannot be obtained from the metal vapor plasma because the gas-vapor mixture and density are not known. Also, care must be exercised in interpreting temperature profiles when the measured intensity profiles deviate significantly from a Gaussian or error curve shape (the radial distribution resulting from the inversion of a Gaussian profile is a Gaussian). An example of the extent of error which may be encountered is given in Appendix B.

Conclusions and Summary

Despite difficulties such as arc fluctuations and limited observation time encountered in performing spectroscopic measurements on welding arcs during actual welds, the techniques developed in the course of this work provide increased detail of information not available from total arc current and voltage measurements. The argon intensity-maximum method, which provides radial distributions of temperature and current density, is primarily useful in studying effects of electrode shape and weld groove design in conjunction with a water cooled copper anode. Such studies are facilitated greatly by use of the OMA®. For welds on metals which do not contain excessive quantities of high vapor pressure materials (such as manganese), this technique, because of the data gathering speed of the OMA®, is useful for the study of the welding process.

The argon ion line intensity ratio method is particularly useful for monitoring temperatures on the axis of the arc during a weld when metal vapors from the pool rise to the point in the arc that is of interest. In the region of the arc nearest the weld pool, the spectra of the elements in the vaporized base metal must be used. Temperature measurements are made by the line intensity ratio method to provide temperature profiles directly from the observed intensity profiles. Radial temperature distributions can be obtained from averaged intensity profiles which reduce the effects of fluctuations on the symmetry of the light emitting volume. There is a residual error in such distributions because of the steady-state circular asymmetry resulting from the motion of the arc along the joint. This remaining error is of less concern if relative rather than absolute characteristics of the arcs are desired.

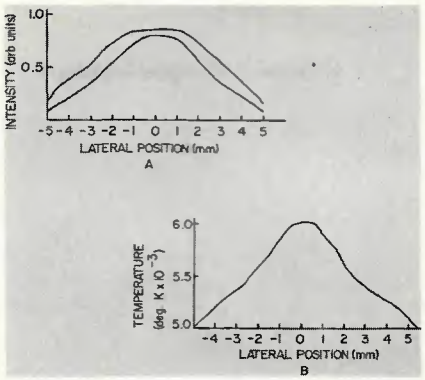

Fig. 3—Intensity profiles of the 5341 angstroms (upper) and 5377 angstroms (lower) lines of manganese (A); temperature profile calculated from the ratio of intensities (B)

Regardless of the special problems encountered, measurements in the metal vapor plasma are particularly valuable because this region of the arc is most directly related to the molten pool and the heat input to it. Finally, it should be noted that all three spectroscopic measurement techniques discussed here can be adapted to arcs shielded with pure helium or helium-argon mixtures.

Appendix A

Spectroscopic determinations of plasma temperature are greatly simplified if they are based on relative rather than absolute measurements of the light energy emitted at a particular wavelength. This can be accomplished if a certain temperature is associated with a particular (characteristic) value contained in a set of intensity data. To see this, consider the equation for the signal strength resulting from emission at a given wavelength from a unit volume of plasma:

$$S = G\left(\frac{A_{kl}}{\lambda_{kl}}\right)\left(\frac{g_k}{g_o}\right) \times$$

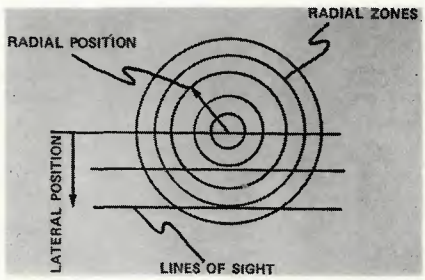

Fig. 4—Example of a transverse section through the arc (perpendicular to the electrode) showing typical lines of sight for experimental measurements and concentric radial zones of equal temperature and density

$$N_i \exp(-eV_{ek}/KT) \quad (A1)$$

In this equation, G is a constant involving the sensitivity of the detector, solid angle subtended by the detector and other constants; A_{kl} is the transition probability associated with the emission line resulting from an electron dropping from the k^{th} to the l^{th} energy level; λ_{Kl} is the wavelength of that line; g_k and g_o are statistical factors denoting the number of electrons which can occupy level k and the ground level respectively; N_i is the number per unit volume of the i^{th} species; e is the electronic charge; V_{ek} is the excitation potential of the k^{th} level; K is Boltzmann's constant, and T is the plasma temperature in degrees Kelvin.

All of these quantities except G, N_i and T (which is to be determined) can be obtained from the literature, and N_i can be calculated for any value of T if the gas pressure is known (typically atmospheric pressure). To eliminate G, relative values of S are calculated from equation (A1) over a suitable range of T values. As T increases, S increases initially because of the exponential dependence, but eventually a maximum in S will be obtained because of the decrease in N_i resulting from ionization of the i^{th} species to the $(i + 1)^{th}$ species. For instance, the density of neutral atoms will decrease as the density of ions increases with rising temperature. The value of T at which this maximum S occurs is labeled T* for which the following relationship holds:

$$\frac{S}{S^*} = \frac{N_i \exp(-eV_{ek}/KT)}{N_i^* \exp(-eV_{ek}/KT^*)} \quad (A2)$$

S* and N_i* are the values of S and N_i at T*. The values of the right side of equation (A2) can be tabulated as a function of T for convenience in determining the temperature from experimental values of S/S*.

The determination of true values of S/S* is complicated by the fact that spectroscopic observations are made along a line of sight passing through the plasma. The intensity of light emitted at each point along this line varies because the temperature and density are far from constant, particularly along a line that lies near the center of the arc. To overcome this difficulty, a transverse section through the arc is conceptually divided into concentric zones having the same temperature (and density), Fig. 4. The intensity along any of the lines of sight indicated in the figure will be the sum of contributions from the zones intersected which has the form of Abel's integral:

$$F(y) = 2\int_{y}^{R} \frac{f(r)rdr}{(r^2 - y^2)^{1/2}} \qquad (A3)$$

If R is chosen so there is no light emitted beyond this enclosed volume, equation (A3) can be inverted analytically to give:

$$f(r) = \frac{1}{\pi} \int_{r}^{R} \frac{(dF/dy)dy}{(y^2 - r^2)^{1/2}} \qquad (A4)$$

A number of numerical methods for performing this inversion have been developed in the past which involve taking a series of measurements, F(y), covering the half-width of the arc, multiplying these values by tabulated coefficients and summing the products to obtain a set of values of intensity as a function of arc radius. The details of this method and a set of coefficients can be found in a paper by W. L. Barr (Ref. 3).

If a transverse section through the arc is chosen such that the maximum temperature exceeds T*, the set of intensities obtained from the above inversion will exhibit the maximum value against which the other values are ratioed to obtain S/S*. If the arc being studied is stable, measurements can be made at multiple levels along the axis of the arc and temperatures calculated over the whole volume of the arc plasma. The same maximum intensity can be used for S* in planes in which T* is not reached (nearer the anode) to calculate S/S* from the intensities in this plane. This is the technique used by Olsen, taking data over several hours; clearly data must be acquired much more rapidly if such information is to be obtained in the presence of the fluctuations associated with arcs run on molten pools.

Appendix B

Rather than try to average experimental line intensity profiles over long periods of time and invert them by the method discussed in Appendix A, a reverse approach is possible which is much simpler. The radiation equation can be integrated numerically assuming various temperature and density distributions, and the intensity profiles calculated can be ratioed to yield temperature profiles simulating the experimental results. This method is preferable because the results of the inversion process (Appendix A) and temperature calculations are very sensitive to small errors in the experimental data while the changes in calculated profiles are determined by the gross features of the assumed distributions.

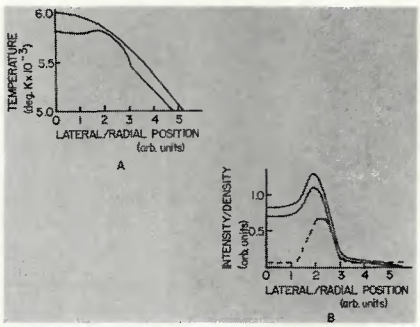

Fig. 5—Assumed radial temperature distribution (upper) and calculated temperature profile (A); calculated intensity profiles (solid lines) and assumed relative radial density distribution (B)

The radiation equation in differential form is given by:

$$dI = -IX\,ds + J\,ds \qquad (B1)$$

in which I is the light intensity radiated along a line s, X is the coefficient for reabsorption of the light and J is the coefficient for emission including stimulated and spontaneous emission. Using the Einstein relationships, these coefficients can be calculated in terms of the transition probabilities mentioned in Appendix A (equation A1) and the number densities of atoms in the upper and lower levels of the transition (line) being considered. For the two manganese lines employed in this work, equation (B1) takes the form of equations (B2) and (B3), as shown below:

$$\Delta I_{5341} = \left[I_{5341}\,(1 - \exp[2.31/V(i)]) + 2.60 \times 10^{-3}\right] \times (8.76 \times 10^{-19})\,N(i) \exp[-4.42/V(i)]\,\Delta S \qquad (B2)$$

$$\Delta I_{5377} = \left[I_{5377}\,(1 - \exp[2.29/V(i)]) + 2.55 \times 10^{-3}\right] \times (2.30 \times 10^{-17}) \times N(i) \exp[-6.12/V(i)]\,\Delta S \qquad (B3)$$

In these equations (B2 and B3), V(i) and N(i) are values of temperature (in electron volts) and density taken from the assumed radial distributions. The sum of these increments of intensity along a chosen line of sight is calculated with a digital computer using the values of ΔS appropriate to the particular line of sight and to radial zones it transverses (Fig. 4). An example of the distortion which can be induced in a temperature profile by a distortion in the density distribution is shown in Fig. 5. The general conclusion here is that distortions in the intensity profiles brought about by anomalies in the density distribution can carry over into the temperature profile calculated from the intensity ratios. This result is true regardless of whether the input temperature distribution is assumed to be parabolic or Gaussian (as in this case). Thus, the significance which may be attached to changes in the temperature profile is limited when the intensity profiles deviate strongly from a Gaussian (error curve) shape.

Acknowledgement

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