A Model of Full Penetration Arc-Welding for Control System Design

D. E. Hardt
Assoc. Mem. ASME,

D. A. Garlow

J. B. Weinert

Laboratory for Manufacturing and Productivity,
Massachusetts Institute of Technology,
Cambridge, Mass. 02139

A model of the dynamics of full penetration welding is presented that relates the heat input to the resulting width of the backbead. It is developed from a heat balance using the pool as a control volume, and is applicable primarily to autogenous gas-tungsten arc welding (GTAW). Two means of modulating the input are considered: 1) varying the torch current and 2) varying the torch travel velocity. The proposed model in both cases is first order, but it has non-constant) parameters (i.e., gain and time constant). Regardless of which input is used, the gain and time constant of the system are shown to depend strongly upon the thickness of the material, the preheat temperature, and the nominal torch velocity. These trends were confirmed in a series of open-loop step tests, where gain and time constant were directly measured, and in closed-lop tests, where step and frequency response methods were used. The resulting model permits rational high performance controller design, and the variable parameters of the system suggest the need for parameter adaptive control.

Introduction

The growing use of programmable manipulators and robots in automatic welding systems has emphasized the need for improved control of the basic process of fusion welding. This process is similar to many manufacturing processes in that the outcome is highly dependent upon the properties of the material in use and the conditions under which it is processed. Since neither of these can be well controlled a priori, closed loop control of the weld quality holds the only promise for a fully autonomous high quality welding system.

Although there are many types of weld joint geometries and welding processes, all fusion welds involve the melting and resolidification of the base material (or weldment). The geometry of the weld bead that results is a good indicator of the basic integrity of the weld, and is frequently used as the primary quantity for post-weld inspection. Factors such as metallurgical state of the heat-affected zone next to the bead and the residual stresses in the material are usually secondary in importance to geometric factors.

In this paper the problem of real-time control of weld bead size is addressed for the specific case of full penetration autogenous Gas Tungsten Arc (GTA) welds. This class of welds covers a wide range of applications ranging from the root pass of thick section welds (such as for pipes and pressure vessels) to thin section (<10 mm) welds found in lighter structures and in the welding of sheet metals. Since the weld involves completely melting the cross section, the bead size is defined by both a top and bottom side width. While it has been shown that both dimensions are important to determining the strength of the final joint [1], our work concentrates on the bottom or backbead width, since it is the more difficult to control and is more sensitive to welding condition variations.

A closed-loop backbead width control system is necessary to insure maintenance of a full penetration condition and to reject disturbances. These disturbances can include changes in the thickness of the mating materials, poor fit-up, varying amount of preheat in the material, variable heat sink conditions, and the presence of tack welds. Although there may be direct geometric influences on the arc physics, the common effect of all of these disturbances is a change in the heat transfer environment of the weld. To properly design a control system to account for these disturbances, which will be shown to be parameter rather than state disturbances, it is imperative than an accurate control model of the welding torch–weldment–weld bead plant be available. This paper presents such a model that is developed from a simple heat balance and confirmed by both open and closed-loop response tests.

Background

There have been several attempts to use real-time measurements to provide regulation of weld bead widths, but none have as yet presented a model of the process dynamics in sufficient detail to allow exploration of the true limits of control system performance. In addition, there have been numerous efforts aimed at developing a functional relationship between welding system controls and weld bead geometry.

In the former category, most work has been goal oriented with limited applications in mind. One attempt, which was actually developed for commercial service, was made by

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Nomura et al. [2]. In this system (which involved full penetration submerged arc welding of very thick plates) a series of infrared sensors were placed under a backing plate on the back side of the weld. These were in turn used to modulate the current to maintain a constant state of penetration. However, the actual measurement was temperature rather than bead width, and the measurement was shown to be very sensitive to thickness variations in the material, which resulted in large steady-state errors. This system was used primarily to improve bead dimensional stability, and dynamics were never considered explicitly. A similar system was described by Smith [3] for full penetration GTAW but he used a "step-pulse" control system thus avoiding the continuous regulation problem. Bennet [4] presented a model of this same system but had difficulty achieving good agreement with experiments. Again the major limitation was that temperature rather than geometry was measured.

Most other control system attempts have employed a topside measurement since it is easier to implement with existing devices. Vroman and Brandt [5] used a linear diode array to measure the width of the top bead on a partial penetration weld, and regulated the torch velocity to modulate the heat input. The system succeeded in regulating to the desired width but suffered from a pure delay introduced by having the sensor mounted so as to measure the leading edge of the pool rather than the center. No model of the weld width dynamics was presented, but it appears that the output of the controller was releated to the negative of the error signal so as to achieve the correct sense in the velocity – heat input relationship.

In a paper concerned primarily with an ingenious measurement system, Richardson et al. [6] presented a topside width regulator that used current as the control input quantity. Although limited control system data was presented, the steady state performance was good, but again the dynamics of the system were not investigated.

In an application of model reference system identification, Dornfeld et al. [7] developed an empirical relationship for the dynamics between the touch current and the backside thermal radiation for a Gas Metal Arc (GMA) process. The results indicated that model equations of order 2 gave acceptable fits to the data. Unfortunately this approach did not delineate any relationship between the parameters of the empirical model and physical characteristics of the system, however, it is a feasible means for real-time modeling of welding, which can then be directly incorporated into an adaptive control scheme.

In the category of welding condition-weld geometry relationships, the most comprehensive work is that of Jones [8]. This work represented a map of the effects of specific parametric variations on the geometry of the resulting weld. However, it was essentially a careful compilation of empirical data that is application specific and contains no functional relationships. An earlier, less complete work was that of Jackson and Shrubsall [9] who did present some empirical equations, but neither work considered the dynamics of the process and disturbances were not explicitly considered.

In a completely open loop approach, Hunter et al. [10] took the approach of controlling fillet weld dimension by regulating all the input parameters to an empirically based geometry model. This led to many measurements, but a useful degree of penetration regulation was achieved. However, this system by its very nature was incapable of detecting and correcting for disturbances that are outside its control loop. Also, no mention of system dynamics was made in the paper.

In a tutorial review of control applied to welding, Boughton et al. [11] defined a closed-loop transfer function and showed the role of *additive* disturbances. The latter are then dealt with in a classical fashion by showing that high gains will minimize the disturbance effects. However, actual welding disturbances are not defined and the only mention of a weld pool model is to suggest that it is characterized by a second order transfer function and to speculate on the reasons.

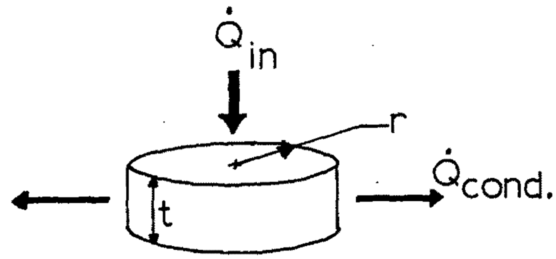

Fig. 1 Assumed weld pool geometry for heat balance

Most of these and other attempts at real-time weld control have had concerns other than the explicit system dynamics (usually the method of output sensing). However, now that several candidate measurement methods are evolving (for example Richardson et al. [6], Zacksenhouse and Hardt [12], Hardt and Katz [13], and Sweet et al, [14]) and the quality of welding equipment is improving, the need for a more detailed understanding of the weld system dynamics is approaching. The following model development and experiments are intended to provide such a control model for the specific case of full penetration welding.

The Model

The model presented in this section is for the case of autogenous GTA butt welding. This implies that no material is added to the weld, and that the two halves of the joint are at the same elevation. However, the causal relationships between input(s) and the output (backbead width) may well extend to situations quite different in weld process and geometry.

Consider the idealized weld pool geometry shown in Fig. 1. This cylindrical shape accurately models a wide, stationary, full penetration weld, but is quite different from the expected geometry when realistic welding velocities and currents are used. However, for the purposes of examining the dynamics of backbead width once full penetration has occurred, this model represents the deviation from a steady state condition where a moving torch continuously encounters and melts solid material. One shortcoming of this geometry, however, is that it assumes that all volume changes in the pool will be detectable from a backbead width measurement, whereas a high torch speed can produce an elongated pool where volume changes may occur mainly in the longitudinal direction.

The model is developed from a simple heat balance, with the following assumptions: the weld pool is isothermal at the melting point of the material, the pool walls remain vertical for all weld widths, the dominant mode of heat transfer is conduction in the weldment, and the thermal dynamics of the solid material are negligible when compared to the dynamics of the pool volume changes caused by weldment liquidification. Accordingly, the heat balance for the system shown in Fig. 1 takes the form:

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{cond.}} + \rho h \frac{dV}{dt} \tag{1}$$

where $\dot{Q}_{\text{in}}$ is the net heat input to the pool, $\dot{Q}_{\text{cond}}$ is the heat conducted through the weldment, and ρ, h, and dV/dt are the density, heat of fusion and rate of change of volume of the pool, respectively. This indicates, as expected, that if $\dot{Q}_{\text{in}}$ and $\dot{Q}_{\text{cond}}$ are equal, the pool will be stationary in size and otherwise will change in volume according to the difference between the heat rates. Thus the actual radius of the weld can be influenced by either the heat input (via the weld torch) or the heat loss, which as will be shown is governed by several factors.

For this idealized cylindrical geometry the heat conducted from the pool can be approximated by considering the temperature gradient across the solid-liquid interface, and the conduction area available. Thus we can derive the pool-radius-dependent conduction term:

$$\dot{Q}_{\text{cond}} = k2\pi tr \ d\theta/dr \tag{2}$$

where k is the thermal conductivity of the weldment, the second term is the radius dependent heat transfer area and $d\theta/dr$ represents a radial temperature gradient.

If we now express the pool volume in equation (1) in terms of the thickness (t) and the cylindrical pool radius (r), and substitute equation (2), we get the desired relationship between heat input and pool width (or radius):

$$(\rho h2\pi tr)dr/dt - (k2\pi t d\theta/dr)r = \dot{Q}_{\text{in}}$$

or

$$C(r,t)dr/dt + G(k,t,d\theta/dr)r = \dot{Q}_{\text{in}} \tag{3}$$

where $C(.)$ is a nonlinear capacitance that varies linearly with the radius and $G(.)$ is a lumped conductance that will vary in proportion to the weldment thickness and the radial temperature gradient. As written in equation (3), the input is $\dot{Q}_{\text{in}}$, the net torch power $= \eta EI$, where $\eta =$ arc efficiency, $E =$ arc potential and $I =$ welding current.

From this simple model it is apparent that although the dynamics of the system are essentially first order, it is in fact a nonlinear system (because of the radius dependent capacitance) and that normally variable quantities such as weldment thickness and radial temperature gradient (which is affected by the torch velocity and degree of weldment preheat) will have a direct effect on the parameters of the system. It is also apparent that variations in the thermal properties (k and h) of the weldment and weld pool will also cause the system parameters to vary.

If we assume for the moment that C and G are constant, and take the Laplace transform of equation (3), we can get a transfer function relating the current (as input) to the pool radius (as output):

$$\frac{R(s)}{I(s)} = \frac{K}{\tau s + 1} \tag{4}$$

where $K = \eta E/G$ and is a gain term; and $\tau = C/G$, and is the system time constant. This transfer function will allow a closed-loop width regulator to be designed given that a nominal welding condition (in terms of t, $d\theta/dr$ and nominal pool radius) is assumed. However, it is important to evaluate how deviations from the assumed operating condition will influence the transfer function and ultimately the width regulator.

The least well defined quantity in the heat balance equation is the temperature gradient $d\theta/dr$, and the ordinary derivative implies that the gradient is independent of the radius along which it is evaluated. If for the moment we ignore this implication, we can see that one direct influence on the gradient will be the average temperature of the weldment before welding. If cold material is being welded the gradient will be large as compared to a warmer or preheated material. Since the lumped conductance term (equation (2)) is proportional to the gradient, a hot weldment should have a lower conductance (and therefore a higher gain) than a cold weldment.

It is also evident that the torch velocity influences the system by changing the lumped conductance term of the heat balance. One important influence is the effect of torch velocity on the temperature distribution in the weldment. The simple line source heat conduction solution presented by Rosenthal [15] can be used for this purpose, and representative top surface isotherms are shown in Fig. 2 for three torch velocities. (Although the Rosenthal solution uses an overly simplistic heat source model and assumes an infinitely thick material, the dependence of these temperature distributions on the velocity can be expected to follow similar trends in

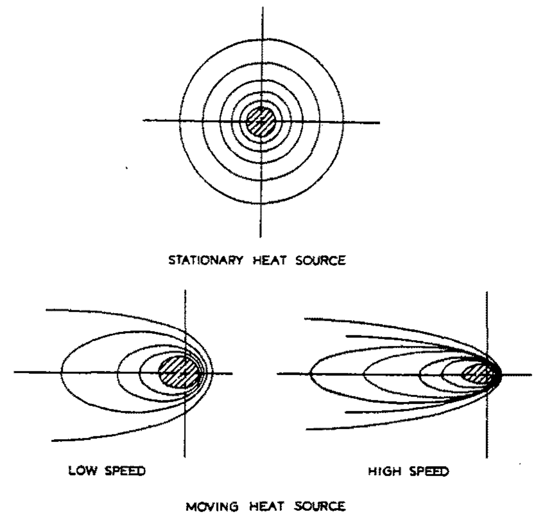

Fig. 2 Weldment surface isotherms as predicted by Rosenthal [15]

actual welding (see Bates and Hardt [16]).) The clear effect of torch velocity is to distort the originally circular, radially symmetric isotherms into patterns that will yield a radial-orientation- dependent gradient. Thus the term $d\theta/dr$ for any finite torch velocity must be considered an average gradient that will depend strongly upon the shape as well as the magnitude of the temperature distributions. It then follows that the torch velocity will directly influence this gradient, and thereby vary the amount of heat conducted away from the pool.

The sense of the velocity gradient relationship can be determined heuristically by considering the difference between a very low velocity, where the material proximal to the pool is preheated by the slowly moving pool, and a very high velocity, where the pool is encountering essentially unheated material. The average gradient should increase as the torch velocity increases, therefore the lumped conductance will decrease with torch velocity.

Although the above suggests that the torch current is the better control variable for width regulation (since it has a more direct and predictable influence on the pool heat balance) it is possible to vary the torch velocity instead of the current to modulate the net heat input to the weldment. (Indeed, if more than one pool dimension is to be controlled it may be necessary to modulate both current and velocity.) To accommodate torch velocity as the input, it is useful to assume an explicit relationship between velocity and the temperature gradient. For the moment our concern will be only the form of the resulting model, which makes exact delineation of the relationship unnecessary. Accordingly, it is assumed that the gradient increases linearly with the velocity:

$$d\theta/dr = K_s v \tag{5}$$

where K_s is a constant that varies directly with the weldment preheat temperature and v is the torch velocity.

Returning to equation (2), substituting equation (5) for the gradient, and rearranging so as to have r appear as the output and v appear as the input, the model becomes

$$\frac{r}{\eta EI - C\dot{r}} = K_g \frac{1}{v} \tag{6}$$

where $K_g = 1/(2\pi tkK_s)$. From equation (6) the highly nonlinear nature of the pool melting dynamics when velocity is the control input is evident. It is also apparent that the proper input is the inverse of the velocity, and that the steady state value of gain for this system:

$$\frac{r}{1/v_{ss}} = K_g \eta EI \tag{7}$$

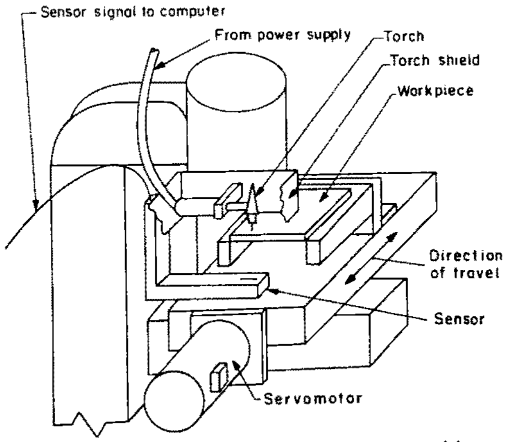

Fig. 3 Computer controlled torch velocity system used for open and closed-loop tests

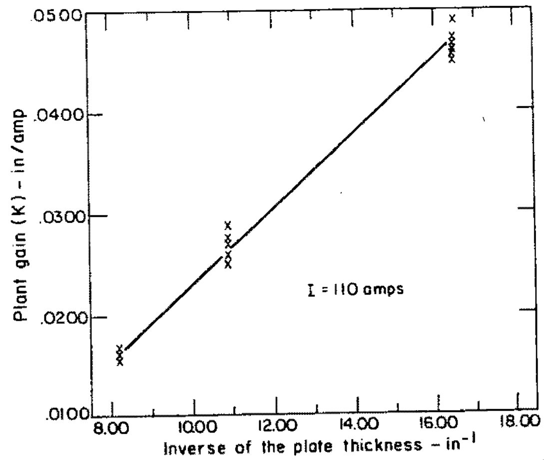

Fig. 5 Plant gain (steady state width/torch velocity) as a function of weldment thickness

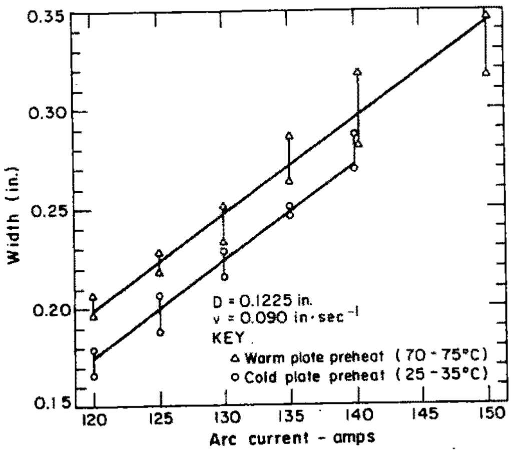

Fig. 4 Weld width as a function of current for different weldment temperatures

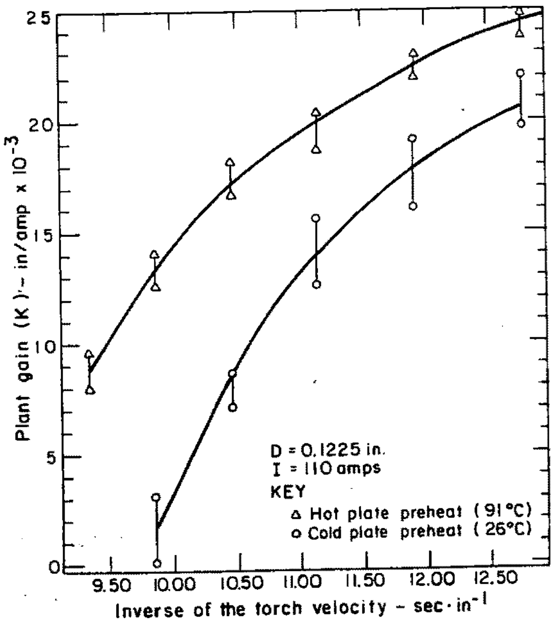

Fig. 6 Current gain as a function of torch velocity

which indicates that under active velocity manipulation the gain is proportional to the torch current.

The form of equation (6) is unsuitable for control system design, and the desire here is to derive a linear model that adequately describes the inverse velocity - pool width relationship. Empirical results [17] indicate that even with velocity modulation the width response to step changes is a simple exponential. This is easily confirmed by inspection of the basic model equation (3) where the step change in velocity translates into a step change in the zeroth order coefficient. The stepwise change in this coefficient will cause the equilibrium point of the system, the system gain and the system time constant to change. However, the latter two will be constant at new values immediately following the step, thus the response of the system to velocity steps will appear first order, but with a magnitude - dependent time constant and gain. For arbitrary inputs, the response will not be as well defined, however, empirical results, some of which are presented below, indicate that in a closed-loop system a variable-parameter first order transfer function relating inverse velocity to backbead width is adequate.

Experiments

The model presented above indicates that when either torch current or velocity is used as the control input, the width response can be described by a first order transfer function, but that the parameters of the system (the time constant and the gain) will be highly variable. To confirm the exact nature of these parameter variations, a series of open loop step tests was performed. The experiments were conducted on a computer controlled welding table (see Fig. 3). The torch velocity was under computer control, and the torch current was determined by an ammeter on the welding power supply. The welding equipment comprised a constant current rectified a-c power supply and a gas cooled GTAW torch operating in a d-c electrode negative (DCEN) mode. The electrode was 1/8 in. diameter 2 percent thoriated tungsten. All weldments were 6 × 24 coupons of 1020 cold rooled steel in various thicknesses and all tests involved full penetration bead-on-plate welds. The plates were mounted along the edges on 1 × 2 in. aluminum bars that served as heat sinks.

For most tests the velocity (rather than the current) was manipulated since the bandwidth of current changes on the power supply was extremely low. For tests concerned with gain measurements the actual backbead width of the weld was measured after completion of the weld. Because the solidified weld has a naturally variable width (owing to the periodic solification of the pool) this measurement involved several measurements on a single weld.

Step tests were performed to determine the system time constant, and an optical sensor was used to obtain a real-time measure of the width. Details of the sensor used can be found in Garlow [17] and Weinert [18], but a brief description is given in the appendix. The output of the width sensor (which

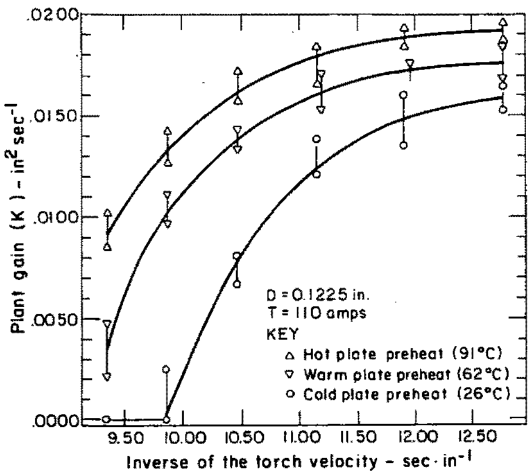

Fig. 7 Velocity gain as a funciton of torch velocity

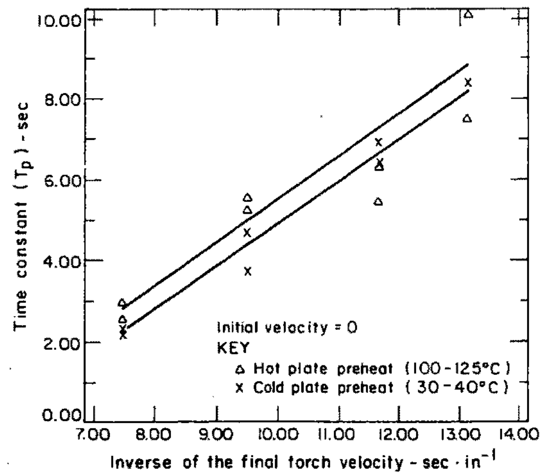

Fig. 8 Plant time constant versus final torch velocity for a fixed initial velocity = 0.0

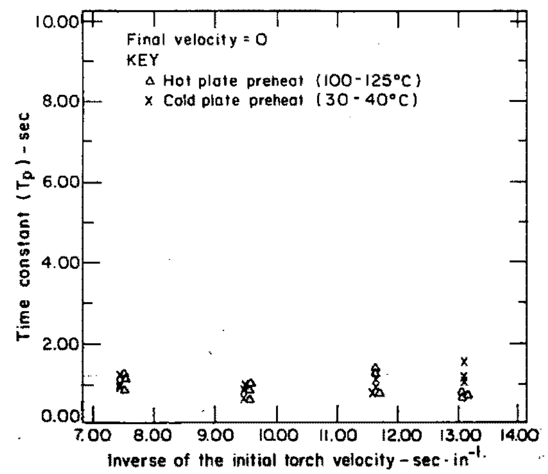

Fig. 9 Plant time constant versus initial torch velocity for a fixed final velocity = 0.0

was analog) was recorded by the control computer and first-order response curves were fit by a least-squares method to determine the time constants.

The System Gain for a Current Input. When the torch current is used as the system input, the gain for this system as defined in equation (4) is given by:

$$K = \eta E/G$$
$$= \eta E/(2\pi tkd\theta/dr) \qquad (8)$$

From this we expect to see an inverse dependence on material thickness and temperature gradient. For the latter this implies (from the above discussion) that the gain will vary inversely with the velocity and directly with the weldment preheat.

Figure 4 is a plot of the steady state width versus current for a constant torch velocity and two different weldment preheats. Since a finite heat input is required to achieve full penetration, it must be kept in mind that the gains defined herein assume a current/velocity bias that represents the incipient full penetration case. It is clear from this plot that the gain is constant for a fixed velocity and preheat, but is scaled directly by the preheat temperature. The result of welding at fixed conditions on three different thickness materials is plotted in Fig. 5. There data confirm the expected inverse relationship between the gain and the material thickness. In Fig. 6 the gain dependence upon the inverse of the torch velocity is plotted. The relationship of gain to the inverse of the velocity is not linear, but it does indicate that the assumption of a direct dependence of $d\theta/dr$ on the velocity is quite valid and that a linear relationship is a good first approximation.

The System Gain for Velocity Inputs. From equation (7) the gain (when velocity is the input) is given by:

$$K = EIK_g = EI/(2\pi tkK_s) \qquad (9)$$

where K_s is assumed to be a function of preheat temperature only. This shows the same dependence upon thickness and preheat as the current gain, however, the assumption of a linear relationship between $d\theta/dr$ and velocity must be tested. In Fig. 7 the measured velocity gain is plotted against the inverse of the velocity. Equation (9) is based on an assumption that this relationship is linear but is clearly not so, thus when using the velocity as the control input the plant will have a nonlinear dependence upon the input.

The Plant Time Constant. When using the current as the input quantity the time constant is defined by the ratio $C/G = CK/\eta E$. If we assume that η and E are constant, variations in the time constant will be governed primarily by the gain variations demonstrated above. However, the model suggests that the capacitance will not be constant but will increase linearly with pool radius. Because the equipment available for experimentation did not permit dynamic variation of the current, an explicit demonstration of the latter relationship was not possible.

When using the velocity as the input quantity the system is highly nonlinear, but since step changes in velocity give exponential response, a first order transfer function relating the output width to the input [inverse] velocity was assumed. Although the gain of this system can be explicitly defined as in equation (7), the definition of the time constant is not evident from the model (equation (6)). However, from the observation that the system is indeed linear for step inputs, an empirical time constant can be measured and correlated to the system environment as was done with the gain.

As observed earlier, when the inverse velocity is the system input, a step change in velocity, by virtue of the change in the pool conductance, will cause a step change in the equilibrium point *and* a change in the time constant. According to this observation, the latter should depend only upon the final velocity of the step and be independent of the initial velocity.

The time constants measured from a series of step tests performed at two values of weldment preheat are shown in Fig. 8 as a function of the final velocity of the step. These results indicate that the final velocity does dictate the time constant, but the effect of preheat is less distinct than with the gain results. As confirmation of the independence of the time constant from the value of the initial velocity, a series of step tests from various initial velocities to a final velocity of zero

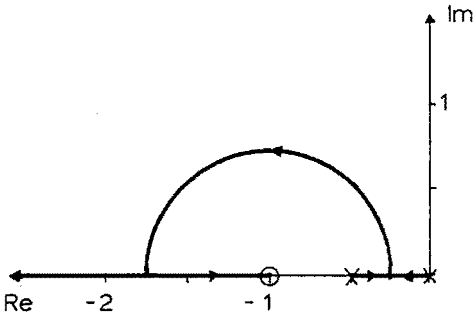

Fig. 10 Root locus for the weld width control system with a PI controller

were performed. These results, shown in Fig. 9 indicate that indeed the initial velocity has no effect on the time constant.

Closed Loop Tests

The purpose of the model presented above is to permit design of a bead width control regulator, and such a system was implemented to afford an additional opportunity to examine the utility of the model itself. While using a closed-loop system can easily mask complex open-loop system effects, the goal here is to examine the trends as predicted by the model and to evaluate their effect on closed-loop control system design.

The control system comprised a CROMEMCO Z2-D, Z-80 based microcomputer executing FORTRAN code, the same torch velocity system described above, and the phototransistor width measurement system described in the appendix. The output of the width sensor was sampled by a 12 bit A/D system and the controller output was sent to a 12 bit D/A to drive the velocity servo.

Since the control model of the plant is first order, and since we have an obvious zero steady-state error specification on the system, the choice for the preliminary controller design was a proportional - integral (PI) form where:

$$G_c(s) = \frac{1/\text{torch velocity}}{\text{width error}} = \frac{K(s+a)}{s}$$

For a first-order plant this should permit arbitrary specification of the system natural frequency and damping ratio, however, when the zero location (a) is fixed the root locus plot in Fig. 10 (drawn for a time constant of 2 seconds, and a zero location of -1) shows that an increase in the gain will initially cause a decrease in the damping, but there is a range during which gain increases are accompanied by an increase in both the damping and natural frequency of the closed-loop system.

A preliminary set of step tests were performed in which a controller was designed with $a = 1$ and with K selected so as to place the roots in this favorable region. While the gain was held fixed, three consecutive step tests were performed, and the resulting responses are shown in Fig. 11. Since the welds were produced on the same piece of material in parallel beads, each successive weld experienced an increase in the weldment preheat, which should cause the plant gain to increase. The resulting step responses show a decrease in overshoot, as would be expected from the gain increase for this system. The increase in the noise level is also indicative of an increase in loop gain since this is low frequency noise inherent in the sensing system and should be amplified by an increase in plant gain. These results are representative of other step test results, and the indication is that the system parameters do indeed change as expected with operating conditions.

In a more direct test of the plant model, a closed-loop frequency response test was performed. (An open-loop test would have been quite difficult because of the highly variable plant parameters since these tests take considerable time to

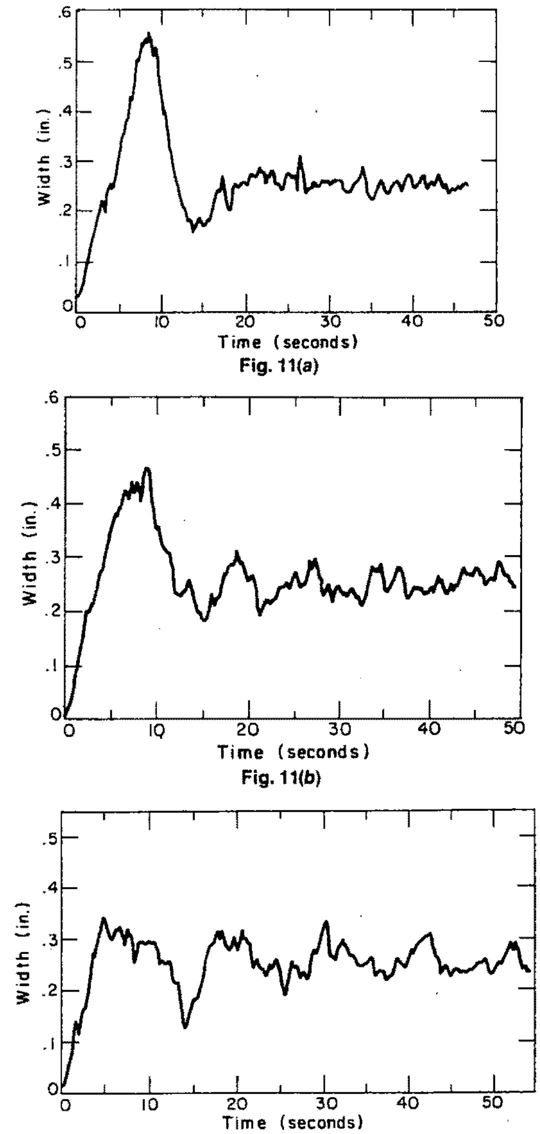

Fig. 11 Response of the width to a step in width command for three weldment preheats (a) 25°C (b) 50°C, (c) 70°C

perform.) Using a controller tuned to the nominal condition used above, a sinusoidal width command was input, and the steady state output (backbead width) recorded. Because of corruption of the output by noise from the sensing system, the actual magnitude was determined by looking at the frequency spectrum of a long sample of the output at each frequency. (The spectrum was found using the FFT method). The resulting magnitude plot is shown in Fig. 12. Although there are deviations from an ideal underdamped second order system with a zero, the -40 dB/decade high frequency asymptote confirms the first order behavior of the plant.

Conclusions

A first-order model has been presented to represent the relationship between the torch current (or the inverse torch velocity) and the time history of the back bead width. Strictly interpreted it should be applied only to full penetration autogenous welds. To extend this model to situations such as tack weld disturbances and to processes where significant filler material is added, explicit consideration of the change in molten material volume must be included. While the simple geometry employed sacrifices some physical fidelity, the resulting model is shown to be causally correct and is

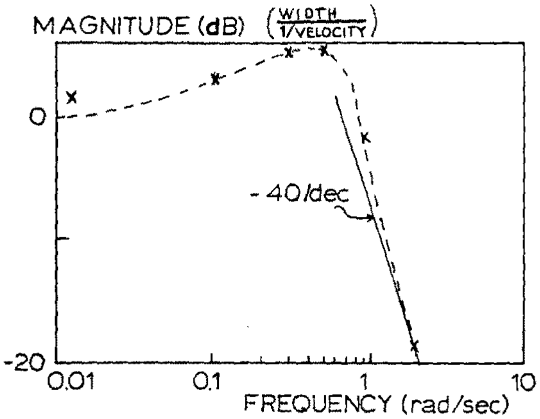

Fig. 12 Frequency response magnitude for the closed-loop system

developed in a form that is useful for control system design. When torch current is used as the input the model indicates that the time constant of the system will increase with the output width and that the gain will increase with the thickness of the material, the preheat of the material and with the inverse of the velocity. When the inverse torch velocity is used as the input, the describing equations are quite non-linear, but empirically the system behaves as if first order. These trends were confirmed by a series of open and closed-loop tests under actual welding conditions, and the sensitivity to the torch speed and weldment preheat were particularly evident.

This simple model permits control systems to be designed in a rational fashion, however, it also indicates that disturbances such as variable preheat, heat sinking, and weldment thickness, will cause the parameters of tne plant to change, thereby affecting the dynamics of the control system. This observation has been confirmed by the closed-loop step tests that were performed. This leads to the conclusion that if high-performance backbead width regulation is desired, the control system used must adapt to these parameter variations so as to keep the system performance constant. This suggests the need for parameter adaptive control, and full penetration weld width regulation presents an excellent candidate for such techniques.

Acknowledgments

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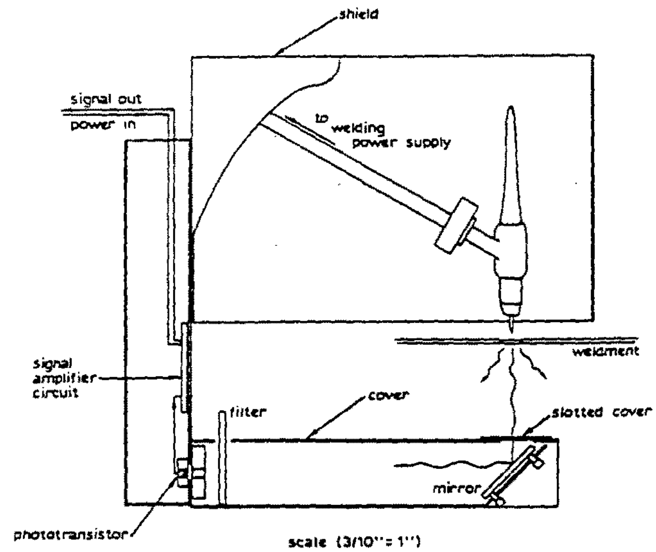

Fig. A-1 The optical backbead width sensor

APPENDIX

The Backbead Width Sensor

The measurement used here to determine the backbead width is the intensity of visible light emitted by the backbead, and the device used is shown in Fig. A-1. The key feature is the narrow slot transverse the weld that confines the view of the sensor to a thin transverse section of the backbead. In this way the light received comes from a well-defined portion of the backbead, and as the width of the bead increases, the amount of light passing through the slot should increase, regardless of changes in other dimensions of the bead. However, the intensity of radiation received will depend not only on the viewing area, but also on the temperature of the bead. In order to provide a simple output from the phototransistor that is receiving the radiation, it is desirable to eliminate the temperature effects. Although this cannot be completely accomplished, it was shown by Garlow [17] that eliminating the infrared portion of the radiation by the use of optical filters, combined with the limited spectral response of the phototransistor, greatly minimizes the temperature effects. As a result, the lower temperature areas that are in view (the unmelted weldment) do not significantly contribute to the output. However, reliable operation still requires that the temperature distribution of the weld pool be constant, which is quite often not true. As a result, this sensor requires frequent calibration, and does inject errors depending upon the size of the weld, the torch travel speed, and the preheat of the weldment. In addition, the presence of impurities on the surface of the molten backbead creates a random fluctuation in the light output, which has frequency components in the range of the system bandwidth.