Arc Welding Penetration Control Using Quantitative Feedback Theory

A feedback control system measures visible and near-infrared light to control joint penetration over a range of welding variables

BY A. E. BENTLEY AND S. J. MARBURGER

ABSTRACT. A feedback control system has been developed for arc weld penetration control. The feedback signal is obtained by measuring the amount of visible and near-infrared light emitted from the backside of the weld. The system is sensitive enough to use a fiber-optic cable for transmitting the light from the weld to the sensor. This facilitates welding assemblies with limited access to the underside of the weld. Welds of constant joint penetration (underbead width) have been demonstrated in tests with travel speeds varying from 1.5 to 6 in./min (0.64–2.54 mm/s), and with 200% changes in part thickness. The system also compensates for sharp discontinuities in heat sinking and arc length. Quantitative feedback theory (QFT) was used to design the control laws.

Introduction

The feedback technique described in this paper was developed for the girth weld of a stainless steel pressure vessel using the gas tungsten arc (GTA) welding process since GTA welding is used extensively throughout the nuclear defense industry. However, the system is applicable to virtually any type of arc welding, and for any part geometry, provided that there is some degree of access to the backside of the weld. For the components designed at Sandia in Livermore, the GTA girth weld is one of the most complicated and critical fabrication processes. If the fusion is not of sufficient quality, often the entire assembly must be discarded.

Modern commercial GTA welding equipment operates under the direction of a welding operator who determines proper machine settings. In more advanced systems, individual weld parameters (weld process inputs) such as arc voltage, weld current, travel speed and wire feed speed are held reasonably constant with feedback control loops; however, set points for the individual weld parameters are selected based on the results of narrow experimental parameter searches, which are expensive even for statistically designed experiments. Weld characteristics (weld process outputs) such as weld width, depth and surface appearance are used as acceptance criteria during the parameter selection process. In this case, however, since visual inspection of the backside of the weld is not possible, these visual cues are supplemented by nondestructive examination with x-rays or ultrasound, and by destructive sectioning, tensile testing and bend testing. While these methods are useful, they do not improve quality, but simply inspect quality, and in the process, add tremendous cost to the product.

The goal of this work is to reduce the need for postweld inspection by implementing real-time joint penetration control. This can be viewed as replacing destructive testing with in-process nondestructive testing (NDT). That is, by utilizing feedback control, weld quality variation can be minimized to the point that inspection becomes unnecessary. Achieving this requires sensor systems capable of accessing weld quality in realtime. As noted by Richardson below, there is currently enormous effort in this area, yet results have been met with limited success:

"Unfortunately, the development of reliable penetration sensors cannot at this time be considered to be broadly successful. This is certainly related to shortcomings of current sensor technologies themselves, but also to the lack of knowledge of how to control penetration once detected. That is, we do not have a good quantitative understanding, in engineering terms, of how control is achieved by manipulation of process parameters in the face of a multiplicity of disturbing variables (Ref. 1)."

Currently, several promising techniques for joint penetration measurement in arc welding have been investigated that only require access to the top side of the weld; however, all except two use indirect assessments of weld joint penetration, and therefore introduce uncertainty into the measurement (Ref. 2). When designing a feedback system, it is important that the uncertainty is restricted to the process being controlled and that virtually no uncertainty exists in the feedback measurement.

The two top side direct joint penetration measurement methods consist of ultrasonic sensing and a newly patented method involving a video camera. The ultrasonic method uses shear waves through the base metal to determine the location of the fusion interface. This method is difficult to implement because of the necessity to couple the transducers to the workpiece and synchronize sensor movement with the electrode motion (Ref. 3). The second method is used in the joining of metal pipes. A small gap is left between the two pipes and a video camera is positioned ahead of the electrode, almost tangent to the workpiece at the weld pool (Ref. 4). This gives a "side view" of the weld and allows the controller to actually "see" the depth of penetration for the first weld pass. It works well for the root pass, but gives no penetration information for the remaining fill passes. One problem we have encountered in the fabrication of

KEY WORDS

Feedback System
Arc Welding
Fiber-Optic Cable
Infrared Light
Travel Speed
Weld Penetration
QFT
Feedback Theory

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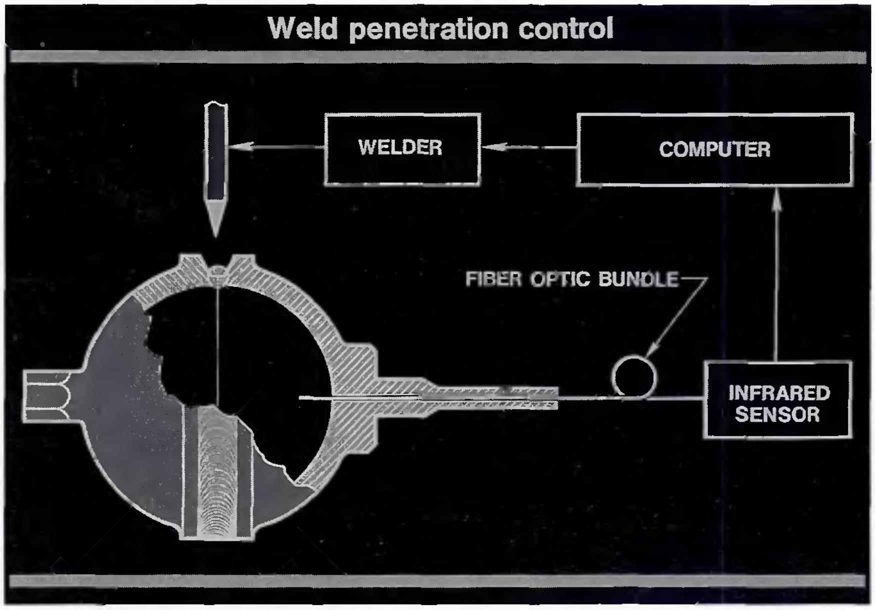


Fig. 1 — Schematic of feedback control system showing a 1/16-in. fiber-optic cable inserted into the pressure vessel.

pressure vessels is called "double drop-through," when full penetration occurs on a fill pass. This is undesirable because it has been found to cause hot cracking in some alloys and may also produce a concave root surface. Therefore, for our application it was necessary for the penetration assessment to apply not only to the root pass, but to the fill passes also.

For our purposes, then, the ideal feedback technique would measure joint penetration directly (including partial penetration) for both root and fill passes. Other investigators have explored two methods for direct measurement from the backside of the weld. The first uses a video camera, or a fiber-optic bundle coupled to a video camera, to obtain an image of the underbead. It then uses elaborate processing techniques to determine the fusion zone width. This not only requires synchronization between the optics and the electrode, but also requires enough access to the backside of the weld to position the camera or insert and position the fiber bundle (Ref. 5).

The other backside measurement technique uses a simple photocell or photodiode to measure radiation, which is related to penetration. The photodiode does not have to be located directly behind the weld if fiber-optic cables are used to direct the light to the photodiode. This is the method that was used for this study since it has the advantage of being the simplest technique to implement, and yet is considered a direct measurement of penetration (Ref. 6). The high-temperature fiber-optic cable used is only 1/16 in. in diameter so it can be inserted into the pressure vessel through the fill tube — Fig. 1. Also note that the vessel doubles as an "integrating sphere" so that the cable does not have to be aimed at the weld. This improves reliability and greatly decreases the measurement complexity by eliminating the need for alignment and synchronization with the electrode.

At Sandia National Laboratories, this technique was pioneered by Marburger (Ref. 7). Initial results were extremely encouraging. The empirically designed feedback system was able to make real-time corrections for large variations in weld parameters to achieve welds of constant penetration. It was found, however, that the relationship between penetration and radiation changed as a function of travel speed. This was attributed to the change in width-to-length ratio of the molten pool for different travel speeds.

The present study more clearly defines the correlation between backside radiation and weld penetration, and accounts for the effect of travel speed on the penetration measurement. Also, with the redesigned feedback control system, GTA welds of more consistent penetration were produced with wider variations in weld parameters including travel speed.

Welding systems are inherently uncertain, nonlinear and time varying in their input/output relationships. Historically, controls have been designed by linearization of system behavior over a narrow range about some operating point. This has produced controllers that are not optimized and/or unstable away from the linearization point. To avoid instabilities away from the linearized region, designers often settle for a reduction in feedback sensitivity and thus do not realize the maximum benefits of feedback. For this work, the control algorithms were developed using a design process called quantitative feedback theory (QFT) that does not require linearization (Ref. 8) and is the ideal tool for design of highly uncertain systems such as welding. Quantitative feedback theory uses information obtained under a wide variety of process conditions to characterize static as well as dynamic process behavior, and encompasses the

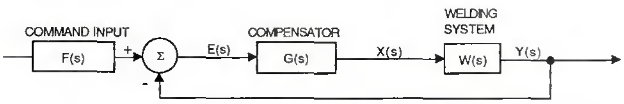


Fig. 2 — Block diagram of feedback system.

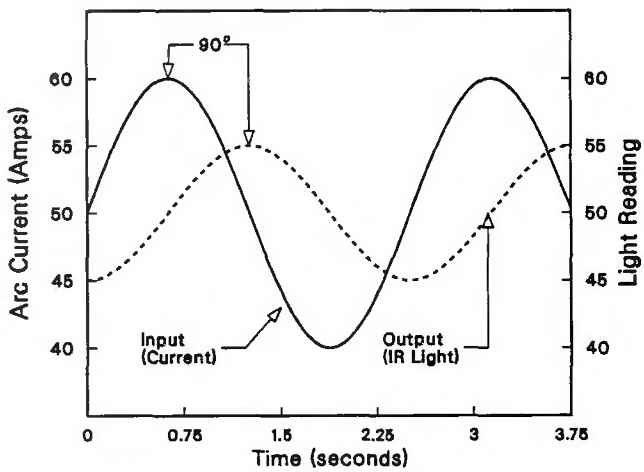


Fig. 3 — Arc weld input (current) and output (light) data.

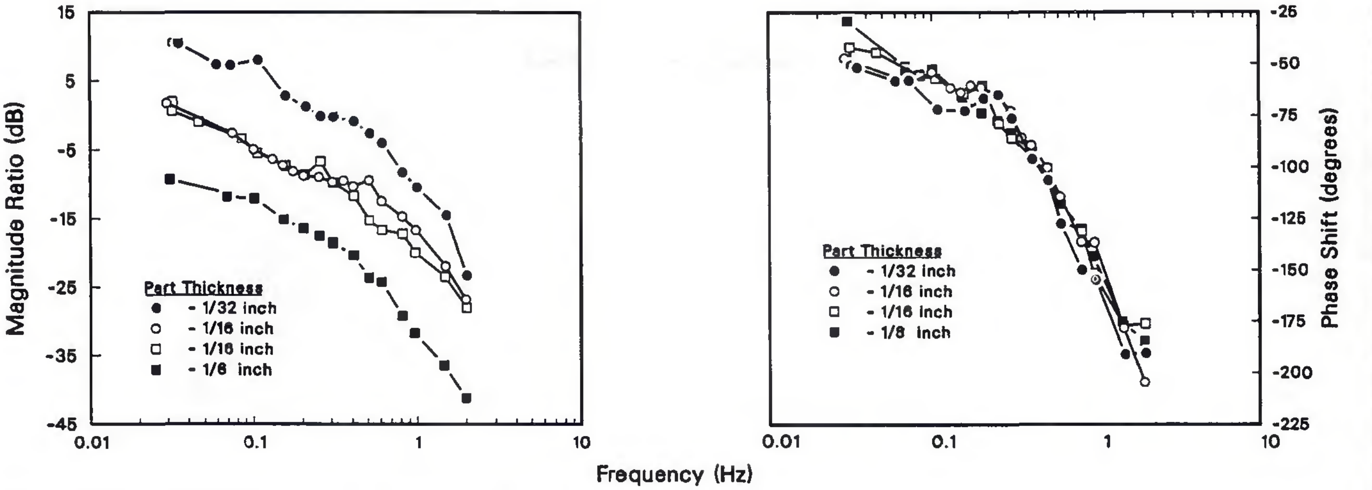


Fig. 4 — Effect of part thickness on arc weld Bode plots.

entire welding system, not just the weld pool or power supply. This global approach yields a controller that is optimized over the entire range of weld performance explored during the process characterization phase, and has proved able to control well beyond the optimized range.

Process Characterization

A simplified block diagram for the control system is shown below in Fig. 2. The output of the system Y(s) (in this case, underbead light) is compared to a desired light level, F(s), for the summer (labeled with the Σ). This error signal E(s) is then passed on to the compensator G(s) and changed into the weld control signal X(s) to make appropriate changes in welding conditions. The changing weld current results in a different light level, closing the feedback loop.

The elements in Fig. 2 are shown as functions of s, implying the use of Laplace transforms. Laplace domain system analysis greatly simplifies control system design, yet it assumes linearity and time invariance, and as stated earlier, welding processes are nonlinear and time varying. However, it has been shown by Horowitz that frequency domain techniques (such as Laplace) can be successfully applied to a large class of nonlinear, uncertain and time varying processes (Refs. 9, 10). The feedback control design tools that make this possible are collectively referred to as quantitative feedback theory.

In order to design the control algorithms F(s) and G(S), information was needed about the dynamic response characteristics of the welding system W(s). This would normally be represented in the form of a transfer function. The transfer function is defined as: "the ratio of the Laplace transform of the output variable to the Laplace transform of the input variable, with all initial conditions assumed to be zero (Ref. 11)." This transfer function provides all the necessary data to properly design feedback control algorithms for the process under consideration.

For this project, it was decided to use weld current as the control variable X(s) to compensate for process disturbances. Varying only the weld current while holding all other inputs constant reduces the system to a single-input/single-output system and the transfer function becomes: W(s) = Y(s)/X(s), where Y(s) is the Laplace transform of penetration (measured in volts on the photodiode) and X(s) is the Laplace transform of the weld current control signal. All other inputs are considered to be process disturbances which add variation or uncertainty to the system equation.

To our knowledge, the transfer function W(s) is not available in the welding literature, but it can be estimated by calculating the ratio of input to output signals (weld current to light reading.) This was done by forcing the weld current to follow a sine wave, and recording the radiated light[1]. A sample is shown in Fig. 3[2] where current and light intensity are plotted vs. time. These data were then used to calculate the ratio between the two signals. There are two parts to this ratio, the first is the magnitude (measured in decibels) and the second is the phase. Note that the light response is delayed in time from the input current. This time shift is the phase portion of the ratio and is measured in degrees. For Fig. 3 the magnitude ratio is one half or –6 dB[3] and the phase is –90 deg. Increasing the frequency of the input variation would increase the phase shift and decrease the magnitude ratio. Collecting this information at several different frequencies produces a Bode plot, which represents a transfer function of the welding system.

Because the welding process is nonlinear and uncertain, each test (even under identical conditions) will produce a different Bode plot. Four such Bode plots are shown in Fig. 4. The data were gathered by making full penetration welds on 1.5-in. (3.8-cm) outside diameter stainless steel tubes[4] while modulating the weld current at various frequencies. The frequency data in Fig. 4

1. *The object of this project is to control joint penetration. Since no purely direct real-time measure of penetration exists, we measure the amount of light from the backside of the weld. This light is measured by amplifying the voltage on the photodiode. No attempt was made to correlate that voltage to units of light energy, since weld penetration is really the variable we want, not light energy.*
2. *Figure 3 shows the input/output information for a single frequency and is not actual data. The actual input data used to test the system was a waveform consisting of several frequencies superimposed together at random phase. Frequency correlation analysis was used to separate out the magnitude and phase information for each frequency individually.*
3. *Magnitude ratio* $= 20 \log_{10}[\text{output/input}] = 20 \log_{10}[5/10] = -6$ *dB.*
4. *The tubes used were readily available and much less expensive than machined pressure vessels. The dynamics of the relationship between the light emitted from the backside of the molten pool and the radiation measured at the sensor is the same for welds made on the tubes as on the actual pressure vessels. The only significant difference between the two is in the reflections of the light inside the vessel, a function of vessel or tube geometry, resulting in a steady-state shift in the light reading. That is, the frequency response for the actual vessels will not be significantly different than that of the tubes except for a shift in light intensity.*

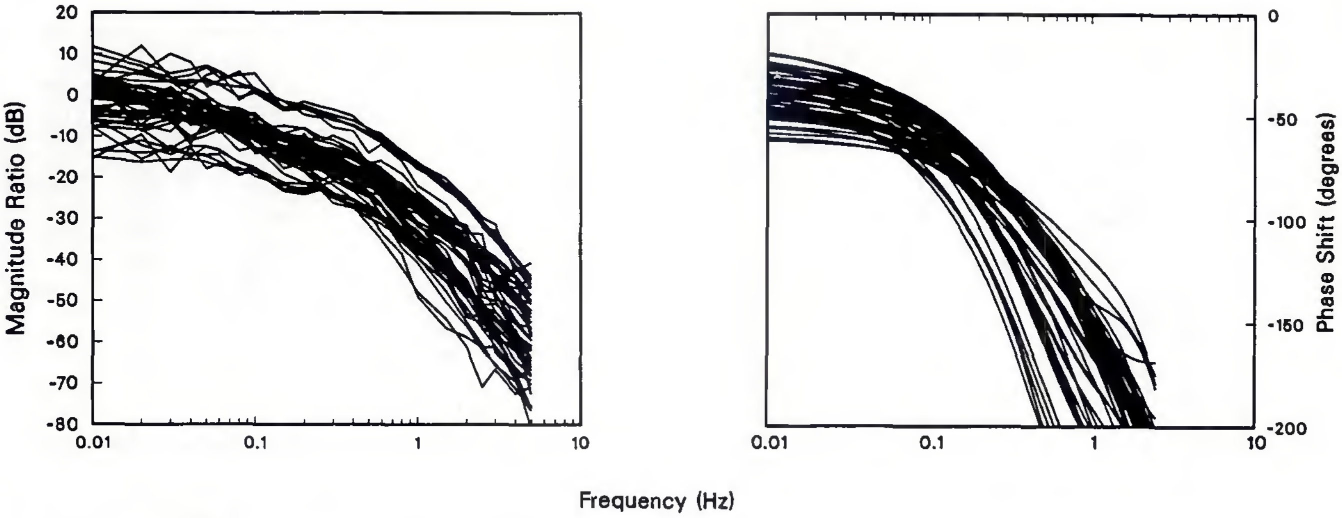


Fig. 5 — Bode plots for 50 arc welds.

are from welds made on tubes of three different wall thicknesses. Note that while the phase information seems to be independent of part thickness (possibly due to the fact that all welds were full penetration), the magnitude changes significantly. This is because it takes less current to penetrate the thinner tubes and minor fluctuations in current will thus yield much greater variations in weld penetration. To further quantify the process uncertainty, more frequency data were obtained for welds made with 50 different combinations of the parameters shown in Table 1.

All welds were autogenous (no filler metal). Material composition was not varied in this initial experiment, but was explored later. Data were taken on both single and multiple pass welds of full and partial joint penetration. The 50 Bode plots produced (Fig. 5) constitute a set of weld transfer functions that span the range of uncertainty in the welding system. (Each weld transfer function will hereafter be referred to as a "plant".) The goal of this project is to design one compensator, G(s), that will produce good welds for any plant within the set of weld transfer functions. That is: at any time the weld may "take on" the dynamic characteristics of any one of the transfer functions (plants) in the set, and the feedback system must adjust the current to maintain constant penetration.

Table 1 — Different Combinations of Parameters below Were Used in the Study

Weld Parameter	Low Setting	High Setting
Transformer tap setting(a)	Low	Medium
Travel speed (in./min)	2.5 (1 mm/s)	4.4 (2 mm/s)
Part thickness (in.)	1/32 (0.8)	1/16 (1.6 mm)
Arc length (in.)	1/16 (1.6 mm)	7/64 (2.8 mm)

(a) Changing the transformer tap setting from low to medium results in twice as much arc current and four times as much power for the same input signal.

Design Procedure

The system was designed for maximum disturbance attenuation and minimum response time, overshoot[5], and complexity. The ideal tool for designing a control system to the above specifications is quantitative feedback theory. This is the only technique known to the authors that rigorously designs highly nonlinear, time-varying and uncertain systems to predefined performance specifications. Therefore, it is the perfect tool for control system design of any industrial process (especially welding) since manufacturing processes are seldom found to be linear-time-invariant with no uncertainty. Quantitative feedback theory is easily understood, simple to apply and makes the design process highly transparent so that the designer can clearly see the performance trade-offs throughout the entire design cycle. Other modern control theories, on the other hand, require proficiency in advanced matrix theory, abstract function space mathematics and matrix algebra.

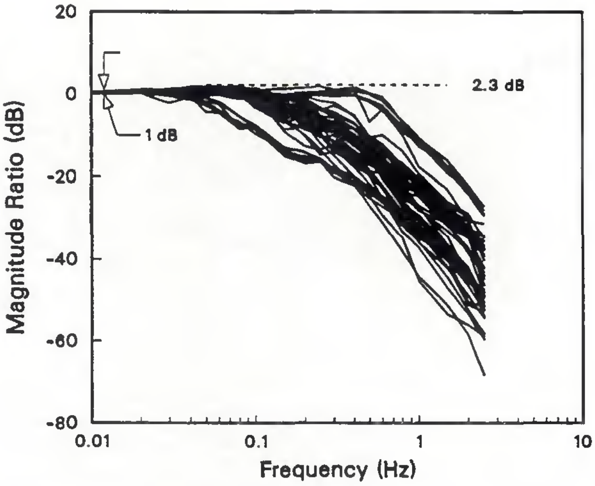
Overshoot can be controlled by insuring that the magnitude of the closed-loop transfer function $|P(f)|$, for each plant in the set, is less than some value γ where: $P(f) = L(f)/[1 + L(f)]$ and $L(f) = G(f) \cdot W(f)$. A typical practice is to design for $\gamma = 2.3$ dB, which, as experience has shown, is associated with minimum overshoot and optimum response times. Assuming the significant process disturbances are primarily low frequency, insensitivity to process disturbances is maximized by minimizing steady-state error — that is: minimum variation of the closed-loop transfer functions $\Delta |P(f)|$ at zero frequency. The smallest frequency for which input/output data were collected was 0.01 Hz, so the system was designed for 1 dB maximum variation at f = 0.01 Hz. That is $\Delta |P(0.01)| \leq 1$ dB — Fig. 6.

The purpose of the compensator (G(s) in Fig. 2) is to "shape" or compensate the open-loop system response so that the closed-loop system meets all design objectives. In other words, the compensator adjusts the welding current in such a way that excessive penetration width is avoided when changes are made to the control setting (minimum overshoot), that the time required to reach the desired penetration is minimized (minimum response time), and that sensitivity to changing heat sinking, travel speed, arc voltage, and other welding inputs is minimized (maximum disturbance attenuation). The closed-loop Bode plot for the 50 welds is shown in Fig. 6. Note that both design criteria are satisfied. Using quantitative feedback theory for design of the compensator[6] yielded the following:

$$G(s) = \frac{53.4(s+0.6)(s+2.2)}{(s+0.016)(s+1.3)(s+36)} \quad (1)$$

The design so far has considered only those control elements needed to minimize system sensitivity to outside dis-

5. *As material is melted, a permanent change in the microstructure and geometry occurs. Therefore, the weld underbead is only controllable in the positive direction, there is no mechanism for causing the fusion zone to "unmelt." Because of this nonlinearity, overshoot must be minimized.*



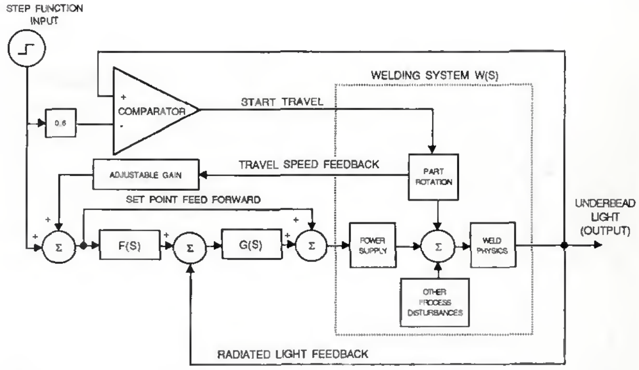


Fig. 7 — Expanded block diagram of feedback system.

Fig. 6 — Closed-loop Bode plots of welds in Fig. 5.

turbances. We now turn our attention to those special provisions needed to establish a stationary full penetration weld and transition into a moving weld while maintaining constant joint penetration. These provisions, namely the prefilter F(s), the set point feed forward loop, the travel speed feedback loop, and the start travel comparator (Fig. 7), also expand the range of disturbances over which the controller can maintain consistent weld quality. The design and operation of these special provisions are best explained by detailing their operation in the complete control system.

In manual welding, the operator first establishes a weld pool, then starts the part rotating, while increasing weld current to maintain the pool size. This is emulated by the expanded control system shown in Fig. 7[7]. Notice the addition of a set point feed forward loop and a travel speed feedback loop.

The system works as follows: at the start, both the travel speed and radiated light signals are zero (since there is no weld to emit light and the part is not rotating). The controller initiates the weld with a 'step function' change in weld current, a sharp change from zero to a predefined nominal current[8]. Initially, the feedback signals, along with the start-up filter output, are zero, so the step function input drives the power supply with the nominal current and the weld pool begins to form. As the weld penetrates the joint, the photometer begins to register light. This signal is fed back and compared to the output of the start-up filter F(s). The start-up filter changes the step function input to a less abruptly rising signal that more closely approximates the process of an establishing and growing weld pool. The difference between the approximated start-up signal and the actual radiated light is called the error signal and is processed by the compensator G(s) and added to the nominal current setting to adjust the weld current control signal. If the weld is responding nominally, the error signal will be small, and the controller will continue to weld at the nominal current. Changes are made to the weld current only when there is a difference between the actual and desired penetration.

When weld penetration reaches the appropriate depth, the controller should start the part rotating[9]. This is accomplished by the start travel signal and travel speed feedback loop. When the light reading reaches 60% of the set point, the comparator starts the part rotating, and the travel speed feedback increases the set point (thereby increasing weld current) to maintain penetration. The magnitude of this adjustment was determined empirically, and is proportional to travel speed. Travel speed variations during welding are also handled in the same manner.

Experimental Results

The system was tested with various disturbances to the welding process to determine how well the controller would be able to maintain penetration. Figure 8 shows two welds made with a step change in travel speed from 1.5 to 6 in./min (0.64 to 2.54 mm/s). (All of the test welds were made on tubes. After welding, the tubes were cut longitudinally and flattened out.) Figure 9 shows that the controller had no problem compensating for step changes in heat sinking, while this disturbance caused large variations in the welds made without feedback. Figure 10 shows the end view of a pipe that was welded to test the system tolerance to changes in part thickness. The system had no trouble welding this part, so in order to further disturb the system, step changes in heat sinking were also added —Fig. 11.

The system was next tested on the tube shown in Fig. 12, which not only introduces step changes in part thickness, but also step changes in arc voltage. (An arc voltage controller was not used, and the electrode was stationary in this test.) The tube was difficult to

6. *For reasons of brevity, the design process will not be discussed in this paper. However, the reader is referred to the June 1991 issue of the* Welding Journal *(pp. 51–63) where Quantitative Feedback Theory (QFT) was introduced to the welding community. A more in-depth explanation of QFT was presented at the 1992 AWS Annual Convention in Chicago.*
7. *Figure 7 is an expansion of Fig. 2. The welding system W(s) has been broken up into four components: The power supply, part rotation motor, weld process uncertainty (disturbances) and the remainder is lumped together under the label 'weld physics.'*
8. *The nominal weld current can be predetermined for each part by the welding operator, or if desired, the operator could guess a nominal current and allow the controller to automatically adjust to the true nominal setting.*
9. *However, the width-to-length ratio of the molten region decreases as travel begins. That is, a traveling weld will produce a molten region that is longer and narrower than a stationary weld. The light signal may be the same, but the weld will be narrower. To maintain constant underbead width, the controller must increase the set point for traveling welds.*
10. *It was later discovered that the ambient radiation read by the sensor was negligible compared to the radiation (both visible and infrared) coming from the backside of the weld. Unless, of course, the ambient light was aimed directly at the sensor or fiber cable.*

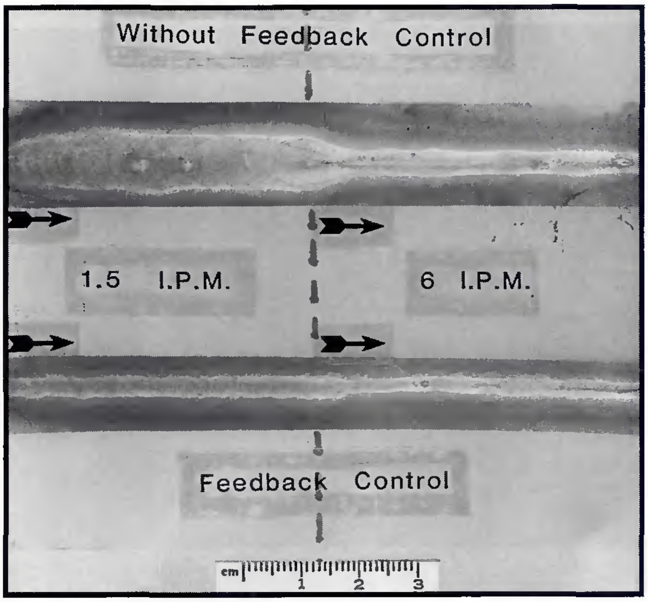


Fig. 8 — Welds made with step changes in travel speed from 1.5 to 6 in./min (0.64–2.54 mm/s).

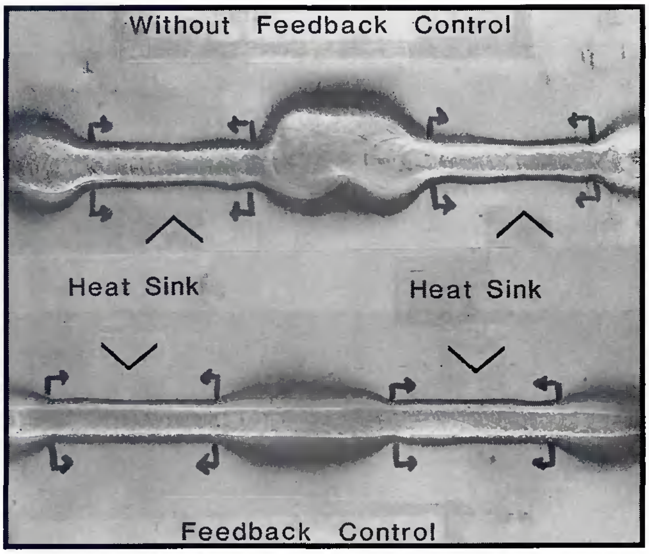


Fig. 9 — Welds made with sudden changes in heat sinking.

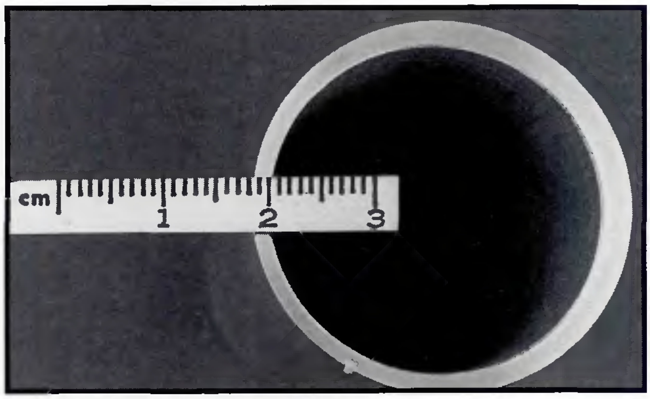


Fig. 10 — End view of variable thickness tube.

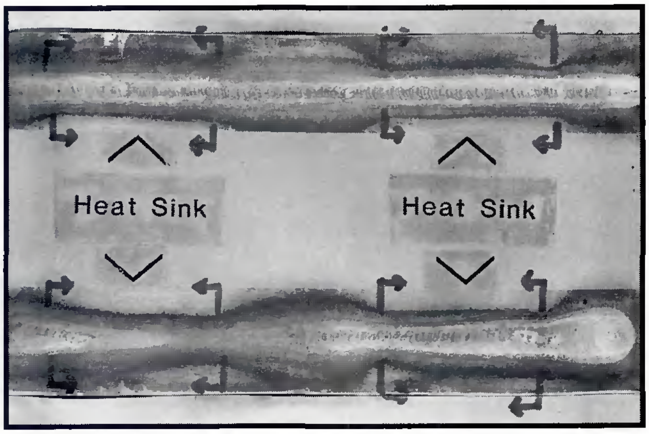


Fig. 11 — Welds made on Fig. 10 tube with changes in heat sinking. Top: With feedback control; lower: without feedback control.

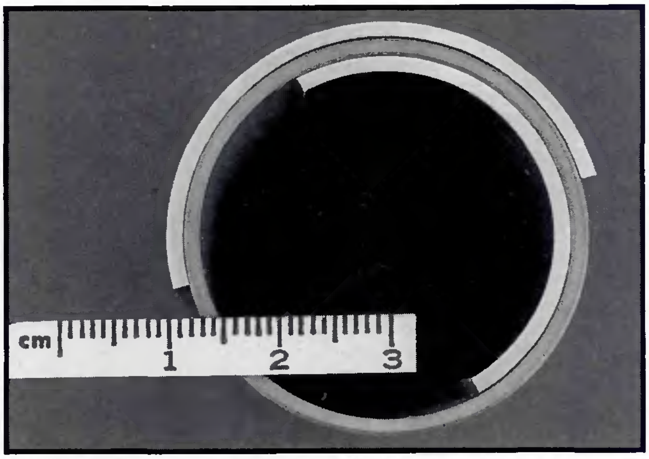


Fig. 12 — Tube with step changes in thickness and arc length.

A B C

Fig. 13 — Welds on Fig. 12 tube (A and B with C without feedback).

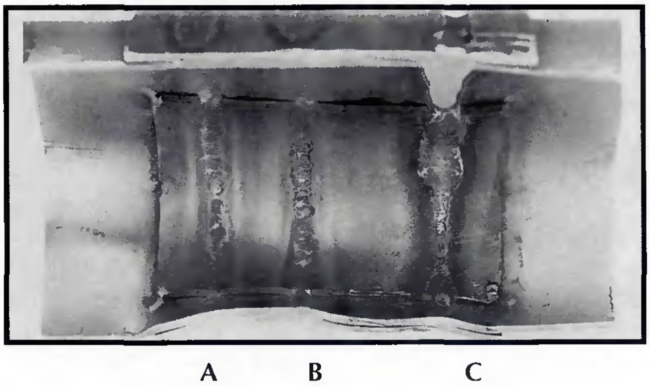


Fig. 14 — Welds on Fig. 12 tube (A and B with C without feedback).

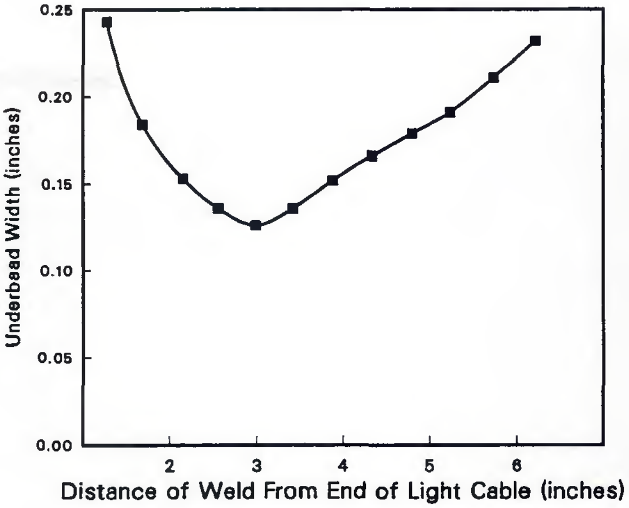


Fig. 15 — The effect of distance on light reading.

flatten out, so the results are shown with two photographs of the same part, taken at different angles — Figs. 13 and 14. The first weld (Weld A in Figs. 13 and 14) compensated remarkably well, except when the weld was coming off the bottom plate where it pulled away from the tube causing light to come from between the bottom plate and the tube, and be interpreted as penetration. The next weld (Weld B) did much better, because the first weld had sealed the bottom plate to the tube, thus preventing the above-mentioned problem. Weld C was made without feedback control.

In order to assess the system sensitivity to sensor positioning, 12 welds were made, on the same tube, at the same set point, but at different distances from the light cable. The width for each weld was measured and is plotted vs. distance in Fig. 15. Although the underbead width variation as a function of distance from the fiber cable was significant, it is clear that positioning the sensor accurately enough to maintain constant penetration will not be difficult. Also note that there is an optimum distance for maximum sensor input, at about 3 in. (7.6 cm) from the end of the light cable.

Originally, there was some concern that with open-groove butt joint welds, the arc light would shine through and be interpreted as penetration. To address this question, several welds were made on tubes with open grooves from 0.03 to 0.09 in. (0.76 to 2.3 mm) wide. For the tubes with the 0.03-in. root opening, weld penetration was unaffected by the presence of the opening. This is most likely because any light coming through the root opening enters the vessel at a right angle to the fiber cable and therefore is not well coupled to the photodiode. The system did have trouble keeping constant penetration with larger openings because a greater portion of arc light was being picked up by the sensor.

Controller Refinements

Once the control system was built, it was possible to make welds of constant backside radiation, and the relationship between travel speed, radiation and underbead width was more accurately quantified. As would be expected, travel speed has a nonlinear effect on the penetration measurement. This is illustrated in Fig. 16. Figure 16 plots underbead width vs. backside radiation for three different travel speeds. Assuming that radiation is proportional to the area of the molten pool, the effect of travel speed on this relationship can be mod-

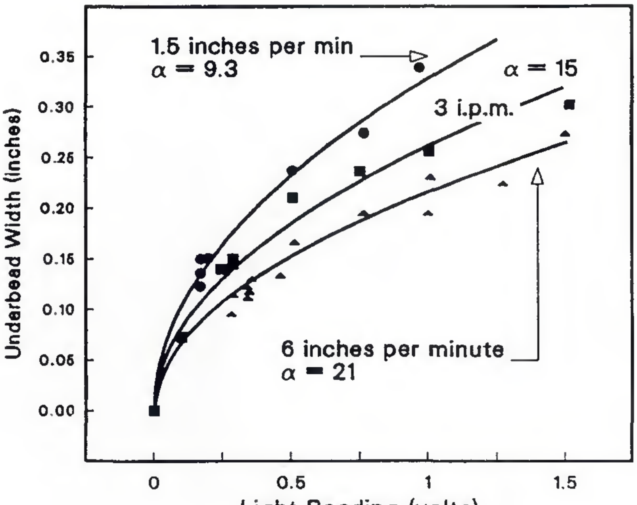


Fig. 16 — Effect of travel speed on the light reading.

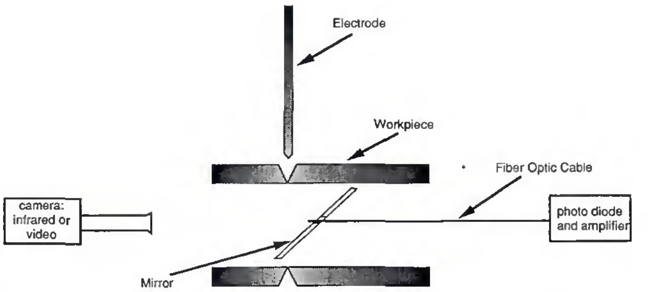


Fig. 17 — Setup for monitoring input to fiber-optic sensor.

Fig. 18 — Infrared video image of stainless steel weld.

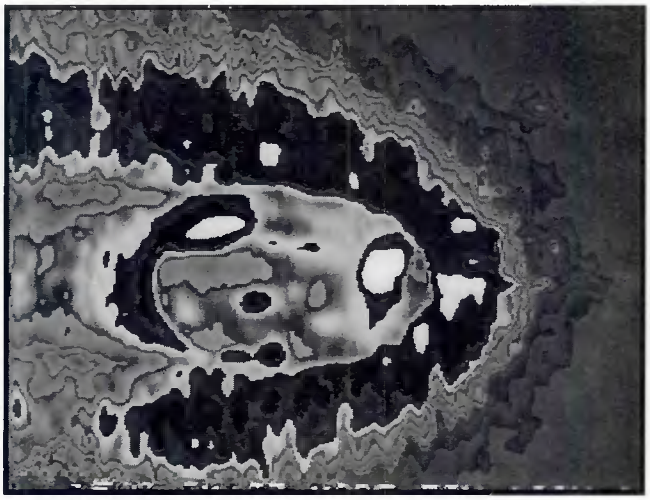


Fig. 19 — Infrared video image of carbon steel weld.

eled. Since the area of an ellipse is proportional to the width W times the length L, the radiation R is also proportional. The width can be measured after the weld is made, but the length must be calculated. For zero travel speed, the length is equal to the width, and increasing the travel speed will cause the length to increase proportionally to the width. Therefore:

$$L = \beta W \qquad (2)$$

Where β is greater than or equal to one, and is a function of travel speed. Then the area (and thus the radiation) is proportional to the width squared. That is:

$$R = \alpha W^2 \qquad (3)$$

The solid lines in Fig. 16 are the result of a least-mean-square fit of Equation 3 to the data from several welds made at 1.5, 3 and 6 in./min (0.64, 1.3 and 2.54 mm/s). The set point adjustment needed to maintain constant penetration with variations in travel speed is different depending on the desired underbead width, and is not simply proportional to travel speed.

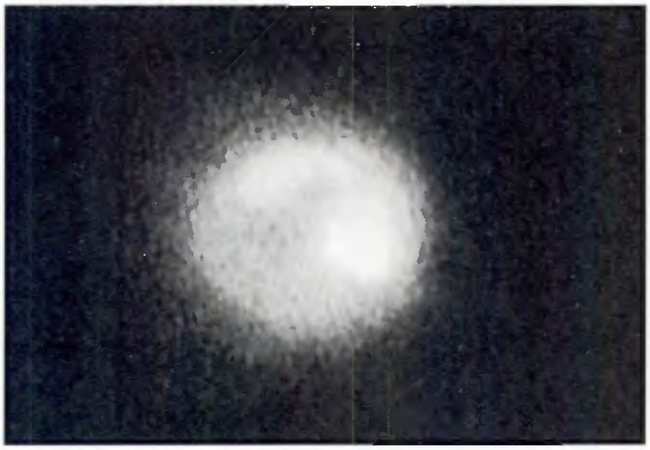
The Nature of Underbead Light

All of the above-mentioned test welds were made on 304 stainless steel. The original system utilized an opaque filter between the end of the fiber cable and the photodiode to attenuate visible light and pass infrared. This was done to remove ambient light from the penetration reading[10]. This worked well until a new application arose for welding on 1020 carbon steel. A large difference was observed in the relationship between backside radiation and penetration for the two different steels. In order to understand this difference an infrared imaging system was set up, as shown in Fig. 17, to determine what the sensor was actually seeing. The infrared images for two welds made on the two different steels, but with identical weld parameters are shown in Figs. 18 and 19. Note that for the carbon steel weld, a much greater portion of the backside radiation came from the area surrounding the fusion zone than for the stainless steel weld. Figure 20 shows the image from a regular video camera on the same carbon steel. Note that the visible underbead radiation is concentrated in the weld pool and thus for controlling weld underbead width, visible radiation is a better feedback parameter than infrared, yet for partial penetration welds, infrared is more significant. For this reason, the opaque filter was removed to allow all available light to pass on to the photodiode.

Conclusions and Future Work

Overall, the backside radiation feedback system worked well in reducing the process sensitivity to changing weld parameters and disturbances. It has been tested with travel speeds ranging from 1.5 to 6 in./min (0.64 to 2.54 mm/s) and with +100% to –50% step changes in part thickness. It also compensates for sharp discontinuities in heat sinking and arc length. Furthermore, the process was found to be reasonably insensitive to fiber-optic cable alignment and position

Fig. 20 — Visible video image of carbon steel weld.



(as long as the cable was not aimed directly at the weld).

The next step will be to use the feedback system for welding actual pressure vessels. This will require penetration control for not only the root pass but also the fill passes. Arc welding systems are inherently noisy (electrically), and are notorious for causing digital electronic equipment to "crash." To eliminate the possibility of the system crashing during a weld, the prototype controller was implemented in analog hardware. An electrically shielded personal computer will be used in future work to implement the control laws. This will facilitate multipass weld control and more accurate compensation for variations in travel speed. It will also make the system more flexible and user friendly. Eventually, the user will be able to specify the part geometry, material composition and desired penetration for the root and fill passes and then use the computer to calculate the corresponding set points that will be needed to make the entire part. It will also be necessary to determine the effects of other disturbances to the system. Specifically, what would be the effects of variations in wire feed rate, material composition, surface preparation, joint geometry, cleanliness and electrode angle and composition.

Many of the problems encountered in welding are related to variations in temperature caused by changes in energy input, heat sinking, misplacement of energy source, etc. This feedback control technique has the potential to reduce or eliminate a number of these and other problems because it tends to maintain the fusion zone at a constant size and temperature. However, additional studies are required to determine what effect the control technique will have on internal voids, the propensity for cracking, cold shunts and other welding problems.

Acknowledgments

The authors wish to thank Dr. Isaac Horowitz of The University of California at Davis who developed Quantitative Feedback Theory (QFT), which made this design both practical and understandable. Modeling and imaging expertise was provided by Lee A. Bertram, William S. Winters and Elizabeth A. Fuchs. Technical assistance was provided by Rich H. Campiotti, Anthony E. Chavez and Dean R. Williams, and special thanks to Antonio J. De Sousa who spent many hours making and evaluating the welds. This investigation was carried out at Sandia National Laboratories in Livermore, Calif. The support of the U.S. Department of Energy under contract DE-AC04-76DP00789 is gratefully acknowledged.

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