

## PHYSICS OF ARC WELDING

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### ABSTRACT

A discussion of the factors controlling the size and shape of the weld fusion zone is presented along with a description of current theories of heat and fluid flow phenomena in the plasma and the molten metal weld pool. Although experimental results confirm that surface tension, plasma jets, and weld pool convection all strongly influence the fusion zone shape; no comprehensive model is available from which to predict welding behavior. It is proposed that the lack of such an understanding is a major impediment to development of automated welding processes. In addition, sensors for weld torch positioning are reviewed in terms of the mechanical and electromagnetic energy spectra which have been used. New developments in this area are also needed in order to advance the technology of automated welding.

### INTRODUCTION

Arc welding technology has evolved empirically over the past half century without the benefit of a true fundamental understanding of the process. Although generally adequate for development of manual welding, this approach is quickly becoming inadequate for automated welding processes where the predictive requirements are greater. The function of an automated welding system can be divided into three categories:

- 1) Systems for control of penetration,
- 2) Systems for positioning the welding torch,
- 3) Systems for control of welding parameters.

It will be shown subsequently that our empirical knowledge of arc welding is insufficient to provide for control of weld penetration; while the torch positioning systems currently in use lack the sophistication necessary to advance welding automation. Systems for controlling the welding parameters lack the sensors needed for control of the process. There are many opportunities for both theoretical and experimental studies aimed at improving our knowledge of the arc welding process.

### CONTROL OF WELD PENETRATION

Figure 1 shows the cross sections of two gas tungsten arc welds, both of which were made with 300 amperes arc current and 12 volts. The weld in Figure 1(a) was made with a travel speed of 0.16 mm per second. The contour is quite different from the 15 second stationary weld of Figure 1(b), which has a hump in the center.

These weld profiles are shown to illustrate the differences which can arise from seemingly minor changes in the welding process.

It has been shown that minor differences in the material also produce significant changes in the fusion zone size and shape. A review of the material variations which result in variable welding behavior has been given by Glickstein.<sup>1</sup> As little as 50 ppm of impurity in the metal can produce a four hundred percent variation in the weld penetration. Commercially this results in a number of problems. One supplier requires the steel mill to perform a spot weld penetration test on all material prior to shipment. Any sheet not fully penetrated within a specified time at fixed current and voltage is rejected. Another fabricator, using automated welding equipment, was unaware of these variations in melting behavior. The defects produced by either insufficient or excessive weld penetration resulted in a \$7M repair on \$4M worth of product. A competitor, knowledgeable about this phenomenon, maintains control by separately inventorying each coil of steel received and establishing welding parameters for each coil individually. The problem is not limited to carbon steels as shown in Figures 1 and 2 but has been observed in titanium, molybdenum, niobium, nickel alloys and stainless steels as well.

Although many theories and experiments have been presented to describe the factors controlling weld penetration, no comprehensive model is available. There is an active discussion in the literature over which factors predominate, yet it is probably safe to conclude that a number of phenomena can control depending on the welding regime and the material under investigation. Most theories relate, either directly or indirectly, to convection within either the plasma or the weld pool. Within the plasma, electromagnetic forces produce a plasma jet travelling at velocities on the order of 100 m/sec<sup>2</sup>. This jet stabilizes the arc giving it stiffness, yet it also may entrain impurities from the surrounding atmosphere<sup>3</sup> as well as produce a depression on the surface of the molten metal pool as shown in Figure 2. The surface depression could easily account for variations in weld pool geometry. This is supported by the observation that highly refined metals, which may have high surface tensions, often produce shallow weld penetration.<sup>4</sup> Contamination of these refined steels with oxygen or sulfur, both of which are surface active elements, produces a large increase in weld penetration depth.

It is also well established that convection in the weld pool can alter the shape of the weld pool. Superposition of external magnetic fields,<sup>5</sup> variation in surface heat distribution<sup>6</sup> and surface tension driven (Marangoni) flows,<sup>7</sup> have all been proposed as the cause of variation in weld penetration. Recent studies have shown that the surface heat distribution may explain the humped stationary weld pool shown in Figure 1(b).<sup>8</sup>

Other explanations for the variation in weld pool shape involve changes in the electrical properties of the plasma due to secondary elements. Glickstein has shown that a small quantity of oxygen in argon can strongly influence melting! Vapor emission from the weld pool<sup>9</sup> can also alter the composition and conductivity of the plasma. Since the welding current transports approximately ninety percent of the sensible heat to the workpiece,<sup>10</sup> any change in

plasma conductivity caused by vapor emission could alter the heat distribution on the surface. Chasell<sup>11</sup> has proposed that the heat transfer efficiency is altered by secondary electron emission into the anode fall region of the arc.

A comprehensive understanding of heat transport in welding arcs is too complex to be solved in even a few studies, however, there are a number of investigations currently in progress. Spectral temperature measurements of the plasma have been attempted on several occasions; however, since most of the heat is transported by the electrons and not by conduction and convection of the hot plasma gases, these studies have met with little success. Chasell<sup>11</sup> has measured anode voltage drops, but again the results showed little correlation with measured penetration. A number of investigators have purposefully added impurities to the surface of the base plate in order to increase the contamination to levels which provide more reproducible results. Unfortunately, the effective impurity elements are usually surface active which means that they are segregated to the grain boundaries during solidification and thus increase the possibility of hot cracking.

In our own laboratory, we are attempting several different approaches. Previous studies of the arc force produced by the plasma jets confirmed that the force increases as the square of the welding current,<sup>2,12</sup> yet the correlation of force with penetration is lacking.<sup>12</sup> Presently, direct measurement of the surface depression using a laser imaging technique<sup>13</sup> is under study, but the results are not yet available. A time gated, high resolution spectrometer has been constructed with two research objectives. Firstly, the temporal and spatial distribution of metal vapor in the plasma will be determined. A typical spectra taken from a 0.1 mm diameter spot over a time period of 0.5 seconds is shown in Figure 3. Manganese and chromium have the highest vapor pressures of any alloys elements in the steel. The remaining lines are all argon.

Secondly, a reflective lens has been designed which will measure the infrared spectra from a 0.1 mm spot on the surface of the weld pool. By switching the arc off with a transistorized welding power supply and measuring the surface temperature distribution and local cooling rate over a time period of  $10^{-2}$  to  $10^{-1}$  seconds, the convection in the weld pool may be estimated. We are also expanding on the measurements of Nestor,<sup>14</sup> in which he used a split copper anode and an Abel inversion technique to measure the heat distribution on the surface. Preliminary results from these heat distribution studies suggest that the maximum heat transfer is not at the center of the arc, but forms an annular ring around the center point. Relatively small changes in the heat distribution can shift the diameter of this annular hot zone. Since a similar effect may be noted for the current distribution on the surface, the effects on convection within the weld pool may be profound. All previous heat flow models have assumed a point source of heat, which in terms of weld pool convection is unrealistic.

Whatever the cause of variations in weld penetration, the final result is unacceptable. Automated welding requires a reproducible weld geometry given a constant set of input parameters. Unfortunately, without a better understanding of the cause of the variations in weld penetration, it is unlikely that we will be able to provide either the constancy of material or the uniformity of parameters that is needed. An approach suggested by some is to provide sensors for adaptive control of the process rather than attempt a constancy of input material to the process. Although this represents a viable approach in principle, the selection of the best weld penetration sensor technology is just as dependent upon an understanding of the physics of the arc welding process as is the proposal for establishing more constant process inputs. Neither solution can be achieved without a better knowledge of the controlling physical phenomena.

Melting droplets from consumable electrodes introduce a number of further complications in prediction of weld pool shape. Although this subject is not reviewed in depth in this paper, it should be noted that there are a number of unsolved questions concerning the forces which dominate convection within the metal droplets, detachment of the molten drop from the electrode, transport of the droplets across the arc and interaction of the droplets with the weld pool. A useful starting point for those interested in this topic is given in the references.<sup>15</sup>

#### CONTROL OF TORCH POSITION

After control of penetration, the next requirement of automated welding technology is torch positioning which is sometimes referred to as seam tracking; however, there are a number of difficulties encountered in following the weld seam. Some of the most obvious are the extreme temperature, thermal gradients and radiation associated with the welding arc. Other less obvious considerations include the fact that the seam is often bridged by previous weld passes and the fact that the seam does not exist at the point of arc contact with the workpiece, hence the sensing must occur ahead of the arc. In order to overcome some of these problems, welding engineers have attempted numerous techniques for seam tracking. These techniques can be described generally by considering both the form and the frequency of energy used by the sensor. Tables I and II show the mechanical and electromagnetic energy spectra respectively.

Referring to Table I, contact probes are available commercially, although they are generally unsophisticated, lacking even a storage memory to permit movement of the torch only after it reaches the discontinuity sensed by the probe. Acoustic and ultrasonic techniques are still in laboratory development. The acoustic sensors use air as the couplant with an array of transmitters and microphones producing a three-dimensional image of the solid metal. Acoustic interference from the arc itself presents a serious problem. Ultrasonic techniques are similar to acoustic techniques except for the fact that the signal is transmitted through the metal. While

not subject to interference from the plasma, wear of the transducers on the metal surface poses another problem.

In the electromagnetic energy spectra, electrical resistance and eddy current probes, both of which are commercially available, are limited by the requirement that the work pieces must be separated by an air gap. This precludes use with multiple pass welding and imposes strict conditions on fixturing of even simple parts. Measurement of the electrical resistance (voltage) of the arc has been commercialized recently. While this technique can be used with multiple pass welding, it places restrictions on the joint geometry and the speed of welding.

Many different thermal and optical weld sensors have been proposed. Perhaps the most promising are optical processes using computer analysis of video images. The thermal processes are generally limited by interference from the arc radiation and by the rate of heat transport in the base metal.

It is interesting to note that several regions of the electromagnetic energy spectrum have not been used for seam tracking. Ultraviolet and higher frequency energy poses obvious health hazards. It is possible that the long wavelength of radio and microwaves would not provide the spatial resolution required; however, there is certainly an opportunity for persons knowledgeable about any of these forms and frequencies of energy to apply their knowledge to the problem of positioning the welding torch within the weld seam.

#### CONCLUSION

An attempt has been made to outline potentials for applications of physics to arc welding technology. The discussion has centered on automated arc welding as it represents the greatest challenge to the welding community today. There is a need for both theoretical and experimental work of both basic and applied nature in plasmas, in heat and fluid flow, in dynamics and in controls. The perspective of the physicist would add greatly to the work of metallurgists and electrical engineers who have dominated the welding field in the past.

Although the scope of this paper did not include laser and electron beam welding, the author wishes to emphasize a need for fundamental physical studies in these areas as well.

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TABLE I. MECHANICAL ENERGY SPECTRA USED FOR WELD SEAM TRACKING

Frequency

$10^0$

$10^2$

$10^4$

$10^6$

$10^8$

Probes

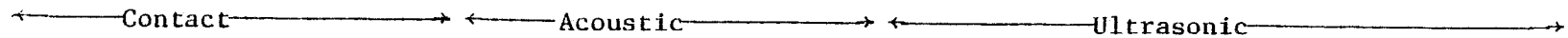
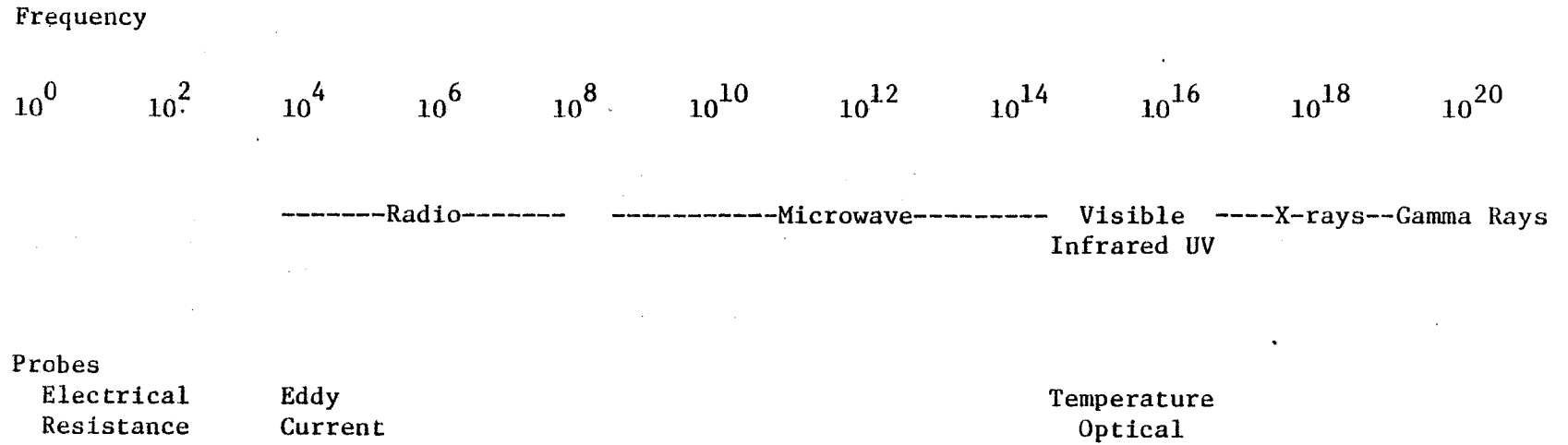
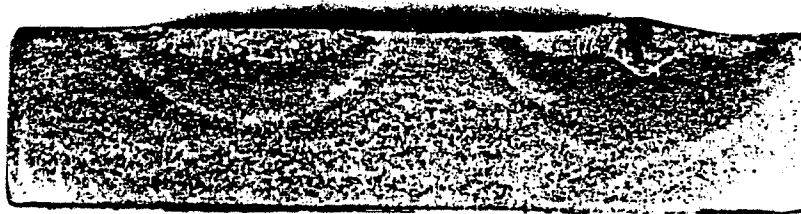


TABLE II. ELECTROMAGNETIC ENERGY SPECTRA USED FOR WELD SEAM TRACKING





1A

1B

Figure 1

Comparison of gas-tungsten arc weld pool shape made on carbon steel with a travelling (A) and a stationary (B) electrode.

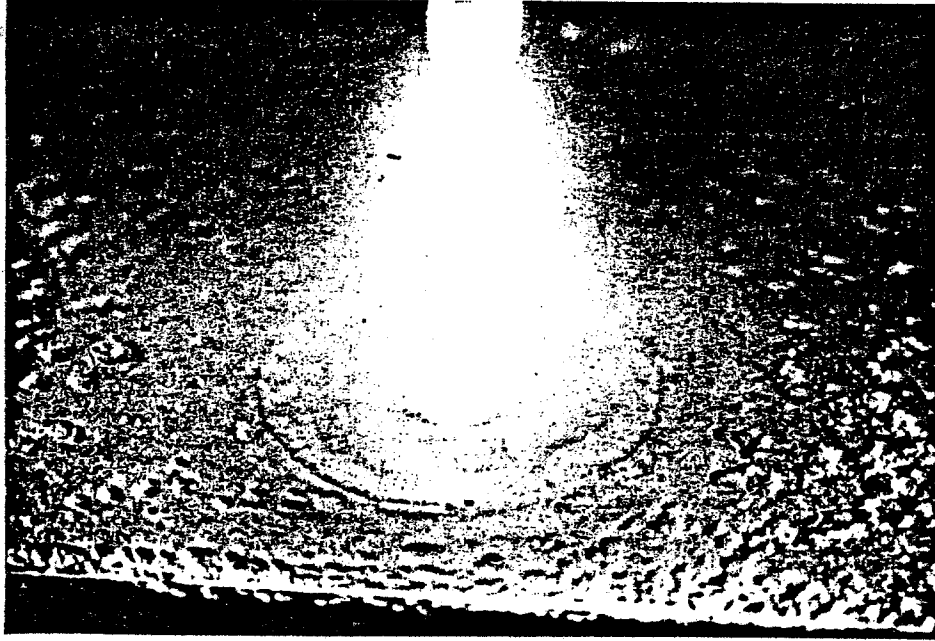


Figure 2

Depression on the surface of the weld pool produced by jet momentum in the plasma.

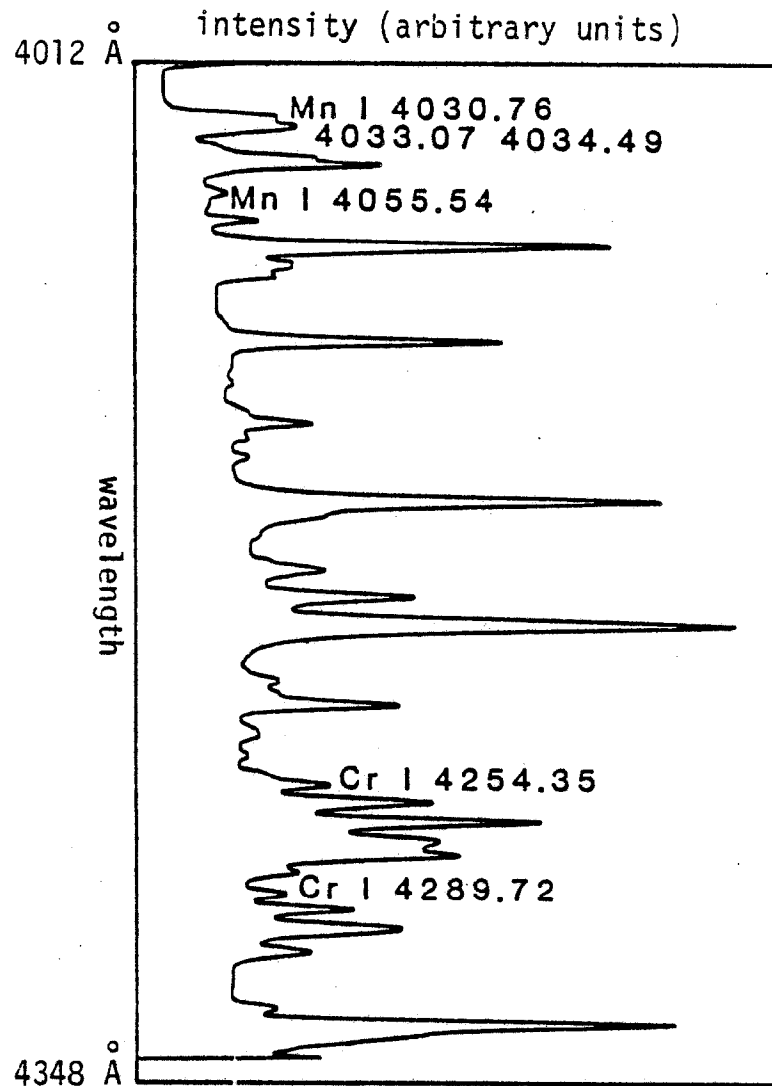


Figure 3

Typical spectrum from 401 nm to 435 nm of as gas tungsten arc on austenitic stainless steel. All of the lines are argon except as noted.