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Study of weld pool formation by real-time radiography with application for sensing and control of arc welding

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The Ohio State University, 1991
STUDY OF WELD POOL FORMATION BY REAL-TIME RADIOGRAPHY
WITH APPLICATION FOR SENSING AND CONTROL OF ARC WELDING

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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To The Guu Family
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CHAPTER I
INTRODUCTION AND OBJECTIVE

Welds on a variety of products can be found almost everywhere on land, at sea, underwater, in the air, and in outer space. It is the ultimate goal of welding process control to achieve good weld quality as well as high weld productivity. For years different control methods for automated welding were used to reach this goal, but lack of direct information on weld quality is the weak point of these methods. A new way to solve the problem is to integrate real-time nondestructive evaluation (NDE) techniques with welding process control techniques.

The conventional (closed-loop) control of the arc welding process regulates one or more welding parameters which are somewhat indirectly related to weld quality [1-12]. Because of the complexity of the welding process and its control [1,13], sensor-based automated welding process control has not been widely accepted in industry. The complexity of the physical relationships and the diversity of the process parameters create difficulties in precision welding. Today weld quality control is still a difficult
task; therefore, inspection of weld quality is required to ensure the serviceability of welded products.

Conventionally the weld is inspected by various NDE techniques in order to characterize the weld quality. Because inspection is done after welding, the time and money spent on weld quality control is added onto the time and money spent on weld production.

Improvement may come from integration of automated inspection with an automated welding process. In this approach, the NDE sensors become a part of the process control system. The information from the NDE sensors is used in feedback loops for weld quality and welding process control. In other words, the NDE procedure is brought forward to the production line to be applied together with the welding process control. This is called "in-process NDE", differentiating it from the conventional off-line (from the standpoint of manufacturing) NDE of welds. Such a method may improve weld quality and provide significant cost reduction [14].

In recent years, the development of high-quality image intensifiers and digital image processing has advanced industrial applications of real-time radiography [15]. Using this technique radiographic images may be viewed on a TV monitor during X-ray exposure time (i.e. real time) of the part being tested. This method produces high-quality, real-
time radiographic images comparable to those from high-quality film radiography. Still, the major industrial application of real-time radiography today is off-line radiographic NDE.

The potential of modern real-time radiography as a vision system in remote arc welding process monitoring and control was first recognized by Rokhlin [16]. The radiographic method differs from optical methods in two ways: (1) there is no effect of the intensity of the welding arc on visibility, and more importantly, (2) changes of thickness and density can be seen, thus providing information necessary for weld quality and process control.

With the unique capabilities of real-time radiography information obtained from the study of the welding process can be utilized to improve the process further and to provide insight for future use. For example, a study of the basic physics of the welding arc and the molten pool and the interactions between them may improve understanding of several aspects of the arc welding process. This has not been investigated due to the lack of proper sensing devices. This method may also assist in investigating the mechanisms of weld formation and in finding the causes of discontinuity formation.
Objective: The goal of this dissertation is to study weld pool formation using real-time radiography for application to in-process sensing and control of arc weld quality. This is the first effort of this type. The applicability and capability of real-time radiography for the sensing and control of arc weld quality are studied and defined. Study of the nonlinear arc plasma-pool interaction at high current levels is needed for this purpose. Studies of the dynamic arc-pool interaction and the stability of the depressed pool surface, which are related to weld and weld discontinuity formation, are also important.

The feasibility of three approaches to weld quality and process control is discussed. The first approach is based on direct information on weld quality extracted from radiographic images during welding. The criteria for determining weld penetration during welding must be obtained. The second approach is based on information extracted from real-time radiographic images of weld pool depression; this is a new approach in weld process control. Finally the first and second approaches are utilized simultaneously, using information on weld quality and pool depression for weld quality and welding process control.

Dissertation Organization: In Chapter II, background information needed for understanding the material presented in the dissertation is provided. General mechanisms of weld
formation are introduced first, followed by serial discussions of the physics of weld formation. Mechanisms of discontinuity formation related to pool depression and instability are also discussed. Past work on arc welding process control using conventional welding sensors and the current state of in-process NDE techniques is also described. A summary is given at the end of the chapter. Advantages and disadvantages of previous methods are discussed.

In Chapter III the concept and implementation of automated weld quality and process control with a real-time radiographic system are described. The idea of using real-time radiography and a balanced arc force measurement apparatus to investigate the arc-pool interaction is introduced to provide a more complete picture of the welding process.

The experimental system developed for in-process weld quality control and for the investigation of the arc-pool interactions (including real-time radiography, welding equipment, and force sensor) is described in Chapters IV and V. Such system characterizations, i.e. determination of contrast sensitivity, resolution and detectability, are described in Chapter IV. For quantitative imaging of the weld pool and weld discontinuities, it is necessary to evaluate the radiographic system for its effectiveness at
revealing pool depression, weld penetration, and weld discontinuity formation.

In order to control weld penetration using real-time radiographic information, the interaction between the arc plasma and the weld pool must be understood. The development of a new technique and a new apparatus for simultaneous real-time measurement of the weld pool surface geometry and the arc force is discussed in Chapter V.

In Chapter V the surface topography of the weld pool is determined from radiographic images using the experimentally determined relationship between image brightness and material thickness. Pool depression and humping on the pool periphery are reconstructed from radiographic images. The arc force is measured using a precision digital scale. To eliminate the effect of X-ray beam shielding by the force-measuring cell, the apparatus is designed in the form of a balance, where the cell is on the side opposite the X-ray beam. The accuracy and repeatability of the force measurement apparatus are found using a specially designed balanced beam and a floating electrical contact between the welding part and the ground. A linear relationship between arc force and current squared is found, which is consistent with theory.

In Chapter VI the arc force and weld pool depression, penetration, and stability are studied by real-time
radiography combined with a balanced force measurement device. The relationships between the welding current, the arc force, the pool depression, and the weld penetration are established. Surface tension and gravitational pressures are calculated from the pool surface topography, surface tension and density. Preliminary results on the stability of the depressed pool are given, and real-time observation of the pore formation in the weld pool is discussed. The complex relationships between welding current, arc plasma force, pool depression, and weld penetration are studied in this chapter. This work lays the foundation for the development (Chapter VII) of new algorithms for weld penetration control and in-process weld quality control.

In Chapter VII the feasibility of in-process weld quality control is discussed based on information on weld quality (the first approach), information on the depressed weld pool (the second approach), and information on both pool depression and weld quality (the third approach). Advantages and disadvantages of using these methods for applications of weld quality control are discussed.

Finally in Chapter VIII, the conclusions of this dissertation are stated and possible areas for future work are suggested.
CHAPTER II
BACKGROUND

The objective of this chapter is to provide the background necessary to understand the material presented in the rest of the dissertation. The current knowledge of the physics of weld formation and the techniques of welding process control using various sensors has been reviewed. The inability to obtain direct information on weld quality in real time is the common problem of conventional welding process control methods. Modern efforts to solve this problem by integrating NDE with welding process control techniques are discussed. In-process ultrasonic NDE of the weld, which parallels the present work in several aspects, is reviewed. A summary is given at the end of this chapter.

2.1 PHYSICAL ASPECTS OF WELD FORMATION

In this section the general mechanisms of weld penetration are described first. This leads next to a discussion of the physics of weld formation. Several physical quantities related to weld formation are also
reviewed, including arc current density distribution, pool temperature distribution, arc force, and material properties. Understanding the effects of these quantities on weld formation is of particular importance for weld quality control.

2.1.1 Mechanisms of Weld Formation: General

The mechanisms of weld penetration have been classified by Ishizaki [17] into two categories: direct digging and indirect melting. The pattern of weld penetration basically depends on several actions taking place in the arc and in the weld pool. These include the arc current distribution, the heat flux distribution, the conduction in the weld pool, the arc plasma pressure distribution, the weld pool depression, and the weld pool motion. Since almost all aspects of weld penetration are included (although some are not yet completely understood), Ishizaki’s work is one of the most complete classifications of weld penetration mechanisms available and is highly recommended by the International Institute of Welding. These classifications are based on where the welding arc strikes.

Direct arc digging on metal implies direct arc plasma heating, arc force, and Joule heating. Obviously the arc force becomes significant at high currents, resulting in a
deeply depressed pool surface. With direct arc heating and high arc current flow, the melting of the metal is greatest, giving deep penetration.

Indirect melting occurs through two other well-known heating processes: conduction and convection [18-23]. Conduction depends on the temperature gradients and the material heat transfer coefficient. Convection takes place in the pool and is driven by a combination of electromagnetic force, surface tension gradients, buoyancy forces, and shear stress. Depending on the dominant driving force, convection in the pool may have varying flow patterns [18,19], giving rise to different levels of weld penetration.

It was also proposed by Ishizaki [17] that a primary and a secondary penetration exists in the molten pool produced by direct digging and indirect melting sources, respectively. In Figure 1 (A), a typical penetration interface and some typical equidepth contour lines are shown which were obtained by hammering during welding. The sectional contour at the deepest point 'E' is the primary penetration, i.e. the maximum depth of penetration. The sectional contours at the widest points 'A' and 'C' are the secondary penetration, which determines the maximum width of the weld bead. Figure 1 (B) shows the two-dimensional cross-sectional pool depression contour at various positions.
Fig. 1- Penetration interface: (A) Penetration interface and equidepth contour lines. (B) Cross-sectional pool contour. (C) Primary and secondary penetration [17].
Figure 1 (C) shows the penetration contours expressed as a combination of the primary and the secondary penetration. Generally speaking, direct digging ensures good weld penetration, which is important to the load capacity of the weld; indirect melting ensures no undercutting, which is a weld discontinuity. This study was qualitative and general.

Direct arc heating and arc force are the dominant weld penetration mechanisms at high current levels. Direct digging has been left relatively unexplored due to lack of proper pool topology measuring devices and because of the complexity of the physics involved. For effective welding process control, specific quantitative information is needed. For this dissertation the relationship between pool depression and weld penetration was studied by using real-time radiography.

2.1.2 Arc Current Density Distribution

The distribution of the arc current density is one of the most important factors in the welding process. It affects all aspects of the welding process, and most importantly, it determines the distributions of both the heat flux and the arc pressure. It also affects pool depression and thus weld penetration.
Fig. 2- Gaussian current density distribution at anode on a flat pool for a 200 A arc [24,25].
Figure 2 shows a flat pool with a Gaussian current density distribution from a 200 amp arc. The data shown in Figure 2 was obtained from a computer simulation of the welding arc done by Choo et al. [24]. Gaussian distributions of the arc current density were also obtained by Nestor [25], using a splitting water-cooled copper anode (no melting). For a Gaussian current density distribution, the pool surface temperature is highest with greatest heat input at the pool center (r=0 in Figure 2) and decreases from the pool center to the boundary. A Gaussian distribution of the arc current density and the heat flux has been widely used for years in studies of the arc welding process. Unfortunately, the effect of current density distribution on pool depression was not studied.

2.1.3 Temperature Distribution In The Weld Pool

In addition to the arc current density distribution, the weld pool temperature distribution is another important factor in the welding process. Temperature is often one of the major factors determining the material properties in the weld pool during welding and is very critical to weld penetration.

Most work involving weld temperature measurements was done in the heat-affected zone. Very little information is
available on the molten pool surface and the internal
temperature. This is because the arc plasma temperature is
extremely high, above 10000 K [26], which prevents
temperature measurements using a contact type sensor like a
thermocouple from being made.

Only recently, several remote measurement techniques
have been applied to measure the pool surface temperature,
including an optical spectral radiometric/laser reflectance
measurement [27] and an infrared pyrometer method [28,29].
The laser reflectance method is based on the definition of
the directional emissivity, Lambert’s cosine law for diffuse
emitters, Planck’s black body spectral distribution of
emissive power, and Kirchhoff’s law for spectral directional
reflectivity. Details can be found in reference [30].

For a flat weld pool, the surface temperature can be
obtained by measuring the spectral directional emissive
power and the spectral directional emissivity at a common
wave length of applied laser light. Figure 3 shows results
of a pool surface temperature measurement. The measured
temperature contours are shown for a steel pool made by a
gas-tungsten-arc welding process with a welding current of
200 A. The pool surface temperatures decrease sharply from a
peak temperature of 2450 K at the pool center to the melting
point at the pool boundary. The peak surface temperature was
as expected found at the center of the pool since the
Fig. 3- Weld pool surface isothermal temperature contours on SS304 for 200 A measured by using the optical spectral radiometric/laser reflectance method [27].
highest current density is also at the center as discussed above. Although no relationship between current and peak surface temperatures were found, the surface temperature distribution could still be mapped.

A slightly higher average surface temperature of about 2500 K (500 K below the boiling temperature) was obtained by computer simulation for a steel pool [31]. A vaporization model was used based on thermodynamic data and the kinetic theory. The results are only an approximation due to insufficient information on surface temperature distributions.

In addition to the pool surface temperature distribution, knowledge of the internal pool temperature distribution is also important to the understanding of weld formation. Measurements of internal pool temperatures for aluminum and copper pools were made under the welding arc by Apps and Milner [32]. Using a thermocouple, pool temperatures were measured 3 and 4 mm below the pool surface. The results are shown in Figure 4 (A) and (B) for aluminum and copper, respectively. It can be seen in Figure 4 that the temperatures measured 3 mm below the weld pool surface were, as expected, higher than at 4 mm because the lesser depth is closer to the heat source. Moving across the weld at the same pool depth (Figure 4), a continuous temperature decrease was found. The highest temperature was
Fig. 4- Temperature distribution in arc-melted pool for (A) Aluminum and (B) Copper [32].
at the center of the pool, while the lowest temperature was located in the heat-affected zone (below the melting point).

2.1.4 Effect of Liquid Metal Properties On Weld Formation

In addition to the current and heat flux distributions, the material properties are important to the formation of the weld through their effects on pool depression and pool convection.

**Pool Depression:** The effects of material surface tension and density on weld formation are described by Equation 1 [26]. Equation 1 was obtained by assuming no pool motion (static) and an infinitely large hemispherical liquid pool. It implies that, at constant arc pressure, pool surface depression depends on material surface tension and density which are strongly temperature dependent.

\[ P = \rho g h + \frac{2\gamma}{R_d} \] (1)

where

- \( P \) is the pressure caused by the arc plasma force.
- \( \rho \) is the material density.
- \( g \) is the acceleration of gravity.
- \( h \) is the depth of penetration.
- \( \gamma \) is the material surface tension.
- \( R_d \) is the radius of the pool depression which is
assumed to be hemispherical.

The surface tension depends strongly on both temperature and composition. In a study using the levitating-drop method [34], the surface tension of two samples of type 316 stainless steel was found to be a linear function of temperature, ranging from the melting point to about 1800° C, as shown in Figure 5. The sulfur level, which is known to be the principal factor affecting the surface properties, of samples A and B were 0.0013 and 0.0152 weight %. The relationship between surface tension and the composition of several surface active elements may be found in [19,23,26,35].

In Figure 5, sample A had higher surface tension and negative temperature coefficient was found due to its lower sulfur content. The higher sulfur level in sample B resulted in low surface tension and positive temperature coefficient. Although the effect of surface tension on weld penetration was not studied, the weld penetration of the low surface tension material (Type B) is expected to be greater according to Equation 1. The empirical relationship between surface tension and temperature is given in Equations 2 and 3 for samples A and B, respectively. The surface tension of liquid iron is about 25 times that of water and about 4 times that of mercury (measured at their melting points).
Fig. 5- Relations between surface tension and temperature for 316 stainless steel [34].
\[ \gamma_{Fe} = 2.814 - 0.574 \times 10^{-3} T; \text{Low Sulphur (A)} \] (2)

\[ \gamma_{Fe} = 1.05 + 0.37 \times 10^{-3} T; \text{High Sulphur (B)} \] (3)

where

\[ \gamma_{Fe} \] is the surface tension of pure iron, N/m.

\[ T \] is temperature, deg. C.

The second material property affecting pool formation is density. In a study using the immersed-sinker method [33], the density of liquid iron was determined over the temperature range of 1800 deg. K to 2500 deg. K as shown in Figure 6. Least-square fitting of the experimental data gave the linear equation, 4:

\[ \rho = 8.523 - 8.358 \times 10^{-4} T \] (4)

where

\[ \rho \] is the density, g/cm³.

\[ T \] is the temperature, deg. K.

The effect of density on weld formation is relatively small compared to the effect of surface tension.

Pool Convection: The effect of properties of the liquid metal pool convection is also important. Surface tension affects the surface flow patterns, and therefore the weld penetration. In a study of the effects of minor surface active elements on GTA fusion zone geometry [19], surface tension driven fluid flow was observed. Figure 7 (A) and (B)
Fig. 6- Dependence of liquid iron density on temperature [33].
Fig. 7 - Surface and subsurface fluid flow. (A) Surface tension temperature coefficient negative. (B) Surface tension temperature coefficient positive [19].
show two different fluid flow patterns for weld pool surface and subsurface flow. In Figure 7 (A) an outward surface flow results in a wide, shallow weld. The outward flow is caused by the temperature gradients along the surface. The temperature gradients occur because the portion of the pool under the arc (at center) is the hottest and the surrounding areas of the pool are relatively cooler. Due to the strong outward surface flow, the weld becomes relatively wide at higher currents. The weld depth-to-width ratio was found by Burgardt and Heiple [23] to decrease as the current increased. These results are shown in Figure 8.

In [19,23], the effects of surface active elements on weld penetration were also studied by adding extra surface elements to the pool. When the composition gradients along the surface are strong enough to reverse the surface tension gradient caused by the temperature gradient, an inward surface flow may occur. This is due to the surface tension at the center of the pool being higher than at the pool boundary. Figure 7 (B) shows a schematic of the effect of surface active elements (for example sulfur) on the surface flow pattern. An inward surface flow and a deep weld can be seen. The dependence of the weld depth-to-width ratio on sulfur and selenium is also shown in Figure 8 [19]. Due to the inward surface flow, the weld depth-to-width ratio is higher than that for outward surface flow. Such effects
Fig. 8- Weld depth-width ratio versus weld current for the starting base metal, sulfur doped zone, and selenium doped zone [23].
become smaller at higher currents as shown in Figure 8. This is probably due to the fact that the pool center becomes even hotter at higher currents and because there is an increase in the amount of impurities vaporized. At even higher currents, the pool depression due to a stronger arc plasma force should have some effect on the weld depth-to-width ratio. When pool depression becomes the dominant factor in weld penetration, an increase in the weld depth-to-width ratio is expected. Unfortunately, current levels above 250 A were not investigated.

Thermal expansion and viscosity may also have some effect on weld formation. The former affects buoyancy in the pool through density change, and the latter affects the speed of the pool motion. Figure 9 shows the relationship between thermal expansion and temperature for 1018 plain carbon steel and 302 stainless steel [36]. An approximately linear relationship between the thermal expansion coefficient and temperature is found for most metals. 1018 steel also shows the effect of phase change on thermal expansion. Viscosity usually decreases as temperature increases, but compared to the surface tension effect the effect of thermal expansion and viscosity on weld penetration is minor.
Fig. 9- Dependence of thermal expansion on temperature for 1018 and 302 stainless steel [36].
2.1.5 Arc Force: Theory and Experiment

Besides the current density distribution and the material properties, the arc force is another physical quantity important in determining weld formation (mainly through pool depression). It is well known that the arc force is generated by the stream of arc plasma which is caused by the electromagnetic interaction between the welding current and its self-generated magnetic field.

The current and the field interact to produce a force on the charge carriers directed inwards towards the arc axis [85]. Under this force the electrons will move towards the arc axis (rather than along the arc axis) and they will collide with the neutral atoms with a collision frequency of the order of $10^{11}$/sec. Thus the electrons carry the neutral atoms with them, creating a local regions of high pressure until the resulting pressure gradients balance the electromagnetic force. When the size of the arc increases toward the workpiece, the pressure decreases, giving rise to a pressure gradient along the length of the arc. The arc plasma flows from the high pressure region to the adjacent low pressure regions. It is expected that a high current and/or a smaller electrode diameter will result in a more intense plasma jet. The arc force has been analyzed analytically, and measured using a force sensor.
Theoretical model: In [37], the welding arc was modelled as a cone, which is close to the real shape of an arc. Figure 10 shows a schematic of the arc. The conical shape is caused by the constriction of the current at the cathode and is related to the welding current. To some extent, the arc expansion may be related to the welding current, and therefore, to the arc force.

As shown in Figure 10 and expressed in Equation 5 below, the arc force is modelled as consisting of two components: a pressure induced force and a momentum generated force. The former is related to the axial current flow and the latter to the radial current flow. In Equation 5, the first term is derived from the pressure force and the second term from the axial momentum.

The axial current component results in a pressure distribution across the arc with peak pressure at the center. As shown in Figure 10 (A), at the narrow end of the arc (cathode), which has a higher current density due to a smaller radius, the pressure is higher than at the wider end of the arc (anode workpiece). A net circulation (plasma jet) results from the pressure difference. Such a pressure distribution produces a force on the plate. The radial current density produces an electromagnetic force (Lorentz force) in the axial direction, which also produces a net axial force on the plasma, called the momentum generated arc
Fig. 10—Plasma jet phenomenon in spreading arc. (A) Pressure distribution. (B) Axial force distribution [37].
force. The combination of the circulation and the net axial force produces the actual flow pattern of the plasma jet. Details of the derivation of Equation 5 are given in the Appendix.

\[ F_{\text{arc}} = \frac{\mu_0 I^2}{8\pi} (1 + 2L\ln \frac{R_2}{R_1}) \]  

where

- \( \mu_0 \) is the magnetic permeability.
- \( I \) is the arc current.
- \( F_{\text{arc}} \) is the force of the conical arc.
- \( R_1 \) and \( R_2 \) are the radii of the arc at the cathode and anode.

According to Equation 5 the pressure induced force always exists but the momentum generated arc force equals zero when \( R_2/R_1 = 1 \). The difficulty of clearly defining and measuring the arc radii and the unknown relationship between arc radii and current leaves the conical arc model unverified. In addition, no effects of other practical welding process parameters, like arc length and pool depression, on the arc force are included in this model. Nevertheless, a relationship between arc force and current square is found to be linear, providing an important basis for the experimental study of the arc force.

**Experimental study:** In [38], laser diagnostics was used
to evaluate the arc plasma velocity. This is based on the Doppler shift of spectral lines using laser lines with the same frequency as the specified atoms in the plasma to stimulate the emission of the arc (resonance scattering). Test particles used in the arc created scattered light pulses, whose frequency was proportional to the velocity component in the axial direction. Figure 11 shows the measured axial plasma velocity distribution \( V_2 \) in the center plane of the arc. Its distribution, as expected, is similar to that of the arc current density of a flat pool (Figure 2). In this study, a water-cooled copper anode was used, but no further study of the plasma velocity distribution was made on a liquid pool.

Experimental measurements of the welding arc force have been conducted using different techniques for the tungsten arc by Savage et al. [39], Burleigh and Eagar [40], and Adonyi [41]. The gas-tungsten arc welding process was selected because no metal deposition is involved and it makes the experimentation relatively simpler. In Savage's work, a linear variable differential transformer (LVDT) was used to measure the displacement then converted to the force, having low force measurement accuracy, about 1.4 grams. In Burleigh and Eagar's work, a torsion bar with low friction was used to measure the arc force. In Adonyi's work, a scale with an accuracy of 0.5 grams was used to
Fig. 11- Axial velocity distribution in the center plane of arc measured by laser diagnostics [38].
measure the arc force where the test plate was directly placed on the scale to measure the arc force. In Burleigh and Eagar’s and Adonyi’s work, subtraction of the non-arc electromagnetic force from the force measured during welding gave the arc force.

Figure 12 shows a comparison of their results. The arc force was found to be proportional to the current squared, except by Savage, and it varied from about 0.2 gram to about 2 grams for welding currents ranging from 100 to 400 A. The arc force measured by Adonyi is slightly higher than that measured by Burleigh and Eagar. In Savage’s work, the unusually high arc force is believed to be the sum of the electromagnetic force and the arc force. Even so, it is difficult to explain the linear relationship between the measured force and the welding current.

The general result of most work is that the measured arc force is proportional to the square of the welding current, which is consistent with theoretical predictions. However, the measured arc force differs from one paper to another, and the measured values are possibly apparatus dependent. This is partially due to the fact that the arc plasma force is about 30% of the total measured force, depending on the experimental arrangement. Also, the effect of pool depression on the welding arc force at high welding currents should be included.
Fig. 12—Comparison of measured arc force [39-41].
2.1.6 Relationship between Pool Depression and Weld Penetration

In this section, the mechanisms of pool depression and the relationship between pool depression and weld penetration have been discussed. It is the flow of the heat in the weld that determines the extent of the pool, and therefore, the shape of the solidified weld. As discussed above, heat flow is governed by several mechanisms. Among these pool depression may have the most important effect on weld penetration, especially at high currents.

The effect of arc pressure and pool surface tension on pool depression and the effect of pool depression on weld penetration were calculated using a finite element method by Friedman [42]. The welding arc was modelled as a source of heat as well as a source of pressure. As far as weld penetration is concerned, such modelling of the welding arc is acceptable. During simulation, the heat input is controlled by the heating time, and the arc pressure is predetermined. Both the heat input and the pressure from the arc are simulated by radially symmetric normal distribution functions. Surface tension is modelled by a membrane with uniform, isotropic tension. An axisymmetric workpiece was assumed, resulting in axisymmetric heat conduction.

The calculated results are shown in Figure 13 where the
increase in weld penetration is plotted as a function of time. Also, in Figure 13 (A), the effects of pool depression on the weld penetration are shown. It can be seen that the weld penetration is greater with than without pool depression (flat pool). The effect of pool depression on the weld penetration becomes greater when the depth of the weld penetration approaches the plate thickness. This is because when there is pool depression the energy from the arc reaches the work at a level below the pool surface such that deeper weld penetration results.

Figure 13 (B) shows the effect of different arc pressure on the weld penetration. Higher arc pressure simulates a higher current (although heat input was assumed independent of current). It can be seen that high pressure results in deeper weld penetration due to increased pool depression. Figure 14 shows the relationship between the predetermined maximum arc pressure and pool depression. The relationship between arc pressure and pool depression was found to be almost linear in the range of partial weld penetration, as shown at the top in Figure 14. When full weld penetration is achieved, the change in pool depression becomes more sensitive to the change in arc pressure.
Fig. 13- Weld penetration. (A) Calculated effect of pool depression on weld penetration. (B) Effect of arc pressure on weld penetration through its effect on pool depression [42].
Fig. 14—Calculated pool depression as a function of arc pressure for various durations of heating [42].
In addition to the arc pressure, the effect of pool surface tension on weld penetration was also calculated in [42]. The results are shown in Figure 15. In this study, constant arc pressure was assumed. As expected, weld penetration was found to be greater for the pool with lower surface tension. This is also because of a greater pool depression. For materials with lower surface tension, the pool surface becomes easier to depress. Basically, Friedman’s simulation is a study of the effects of pool depression (affected by arc pressure and material surface tension) on weld penetration. Other mechanisms of pool depression besides arc pressure were not studied.

In a study of pool depression using Equation 1 [53], Lin and Eagar found that the small measured arc force alone could not explain the deeply depressed pool surface. The existence of a compound vortex in the weld pool was proposed to explain the deep pool depression. As shown in Figure 16 (A), a compound vortex including free (at boundary) and forced (at center) vortices is shown. Since energy is stored in the vortex, a nonlinear hysteresis relation between the pool depression depth and the welding current was found as shown in Figure 16 (B).

The results reported by these authors on mechanisms of pool depression vary. Possibly each mechanism mentioned above has a greater or lesser effect on the formation of
Fig. 15- Calculated effect of surface tension on pool depression [42].
Fig. 16- Pool vortex. (A) Structure of the compound vortex. Assuming no transition region between the forced and free vortex. (B) Variation of pool depression with current [18].
pool depression. In the present work, a real-time experimental study of the arc-pool interactions has improved the understanding of the physics of the arc welding process.

2.1.7 Mechanisms of Weld Discontinuity Formation

As is true for weld formation the mechanisms of weld discontinuity formation are complicated. A general characterization of weld discontinuities may be found in [43,44]. There are more than 30 kinds of weld discontinuities. The causes may be metallurgical, process, geometrical, or design factors. In this section, the causes of porosity and lack of penetration will be discussed, because they are within the scope of the present work. Porosity is related to pool instability, and lack of penetration is related to weld penetration. The causes and cures of other types of discontinuities may be found in more detail in [43].

Porosity: Porosity may be defined as cavity type discontinuities formed by gas entrapment during welding. The primary types include uniformly distributed porosity, localized porosity, aligned porosity, and elongated porosity. The causes relate to the welding process, the welding procedure, and the type and chemistry of the base metal. Porosity may arise during weld fusion and weld
solidification.

The gases which may be present in the pool during welding include \( H_2 \), \( O_2 \), \( N_2 \), \( CO \), \( CO_2 \), \( H_2O \), \( H_2S \), and \( He \) [43,45-52]. Of these hydrogen, oxygen, and nitrogen are soluble in the pool. The contents of these gases may be increased (absorption) or reduced (desorption or degassing) depending on the original content of gas, the solubility in pool and solidified metal, the gas pressure, and the material type [48]. The solubility of these gases in the steel pool is generally greater than the solidified steel [43,48]. This is because the solubility of these gases increases with increasing temperature. Porosity may arise during solidification if the gases do not have time to escape from the pool.

Pool supersaturation, another cause of porosity, may occur as a result of the introduction of gases into the molten metal in excess of solubility limits. Even if excessive gas is not introduced, localized saturation may occur as a result of localized superheating of the pool. In [52], the nitrogen concentration in the metal was found to increase with increasing arc time. Also, the saturation (solubility) limit was found to be dependent on the shielding gas composition, arc current, and arc length. Bubble formation was found to occur in the pool when nitrogen concentration exceeded the saturation limit [52].
Chemical reactions may produce gases which can lead to weld porosity. For example, oxygen present in the pool may react with carbon to form CO or CO$_2$. Oxygen was found to be considerably soluble in the molten weld pool [43] and to exist in the base metal. Oxygen may also enter the molten pool from the shielding gas [45] or the atmosphere. In a series of studies on porosity in mild steel weld metal [45], porosity was found to increase with increasing carbon content as shown in Figure 17. Use of sufficient deoxidizers, such as Si and Al in steel base metal, filler metal, flux, or electrode coating, may decrease the amount of oxygen in the pool and therefore, the porosity.

Another mechanism of porosity formation is related to the weld pool cavity, which can collapse and trap the gases in the weld pool. This was found by Lin and Eagar [53], as shown in Figure 18. In this study, the collapse of the weld pool depression was caused by suddenly extinguishing the arc.

Lack of Penetration: The causes of lack of penetration are more straightforward than those of porosity formation and are related to the welding procedure and conditions. They may include insufficient heat input, incorrect electrode angle, or failure to remove oxides or slag from previously deposited weld beads [43].
Fig. 17- Influence of carbon content on porosity in welds [45].
Fig. 18 - Schematic illustration of liquid metal filling in the crater of a finger penetration weld after the arc is extinguished [53].
Because of lack of proper sensing devices most studies of weld discontinuity formation and lack of penetration were made after weld solidification, giving no real-time information on discontinuity formation. In this dissertation, real-time observation of both weld porosity and lack of penetration has been made possible by real-time radiography.
2.2 SENSING AND CONTROL OF ARC WELDING

The above review indicates that the mechanisms of weld penetration and of weld discontinuity are complicated. The current research has been aimed at sensor-based control of the welding process to produce an acceptable weld.

2.2.1 Direct and Indirect Welding Parameters

Weld quality is related to the welding parameters used. The variables of the welding process have been classified by Richardson [7] into four groups and by Cook et al. [8] into two groups as shown in Figure 19. The direct welding parameters, which are outputs of the welding process, pertain to the weld geometry, mechanical properties, weld microstructure, and discontinuities. They are collectively controlled by the indirect parameters, which are arc welding inputs.

The basic goals of closed-loop control are to continuously sense and control: (1) the welding torch location relative to the weld joint, (2) the geometry of the weld, and (3) discontinuity formation. The ultimate goal should also include control of the mechanical properties and the microstructure of the completed weld [8].
2.2.2 Weld Sensing Techniques

Figure 20 shows a simple closed-loop control system consisting of three basic elements: a controller, the welding process to be controlled, and a welding process sensor. The welding process sensor, which is the key element in weld penetration control, provides the necessary feedback information to the system controller.

Welding sensors have been used mainly for the purpose of seam tracking, welding parameter control, and welding process monitoring [4,9]. Figure 21 shows statistics on the principles and purposes of sensors used in Japan to sense and control arc welding [9]. Optical and arc sensing are important and are increasingly applied.

Optical sensing technology has been developed for years. One of the first real-time optical pool monitoring systems was a coaxial viewing system developed by Richardson et al [10]. With this approach, the weld pool is viewed coaxially with the welding electrode from within the welding torch as shown in Figure 22. Advantages of this system include: (1) the bright core of the welding arc is blocked by the electrode/contact tip, (2) the entire weld area can be viewed without obstruction, and (3) the system is non-intrusive to the weld area and is nondirectional.
Fig. 19- Input and output variables of welding process [8].
Fig. 20- Schematic showing a simple closed-loop control system with system controller, process, and welding sensors.
Arc sensing (or through-the-arc sensing) is based on the changes in current and/or voltage when the arc is moved back and forth across the joint [8]. The obvious advantage of arc sensing is the use of the arc itself as a sensor, so that there is no need for external sensors. This technique has matured over the years and is routinely used on the production floor in automated welding.

Infrared sensing has been used for automatic welding process control based on infrared temperature sensing [5,11,12]. Lukens and Morris [5] have reported the use of infrared sensing for cooling rate measurements and Chen et al. [12] have reported the use of infrared thermography for weld penetration estimation.

2.2.3 Control of Weld Geometry

Weld geometry control is one of the major tasks in welding parameter control and has received great attention in recent years. Control of weld height (face reinforcement), width, and back weld width has been the common goal of sensor-based welding parameter control. Basically, relationships between weld geometries and output signals of various sensors have to be established. Thus, weld geometry may be controlled by regulating the welding parameters.
Fig. 21- Inventions of sensors for arc welding from Japanese patent laid open [9].
Fig. 22— Coaxial arc weld pool viewing system [10].
Weld reinforcement and weld width have been controlled by using arc and optical sensors [3,9,10]. Figure 23 shows the basic principles of the welding process control of weaving GMA welding by using an arc sensor [9]. Basically arc current or voltage changes with the weaving motion of the torch. The measured value in Figure 23 is low at location 'L' and high at locations 'C' and 'R'. By measuring them, the weld height and width can be controlled together with the seam tracking.

Pool oscillation frequency, another application of arc sensing, has been used to control weld size [3,4]. This was done by periodically pulsing the welding current, thus exciting the molten pool into a natural mode of oscillation. The oscillation frequency was found to be inversely proportional to the weld size, as shown in Figure 24 [4]. Welding currents less than 200 A have been tested, and different plate thicknesses have been used for a fully penetrated pool. A full penetration weld pool was found to oscillate several times slower than a partial penetration weld pool of the same width, as shown in Figure 24. This is due to the different constraints on the pool as shown in Figure 25 [3]. The longer wavelength of the full penetration pool oscillation gives a lower natural oscillation frequency. For partially penetrated pools, the oscillation exists on the pool surface. This technique requires a very
Fig. 23— Principle of seam tracking with arc sensor in GMA welding [9].
stable power supply output to allow detection of the small change in arc voltage. The application of the technique has been restricted to low travel speed bead-on-plate or zero-gap butt welds.

Also coaxial arc weld pool monitoring was used to monitor and control weld width directly [10]. An experimentally obtained relationship between the weld width and depth may be used to control weld penetration by regulating the weld width.

For a fully penetrated weld, the control of the back weld width and reinforcement is also important. Arc light intensity, observed by photo sensors the back of the weld, has been used to control the back weld width [9]. This is based on the experimentally obtained relation between the width of the back weld and the detected arc light intensity, as shown in Figure 26 where slightly varied relations of three different kinds of groove conditions are shown. The technique requires the use of additional weld height and face width control techniques.

All of the measured quantities discussed above, except for the direct viewing of the pool surface [10], are only somewhat indirectly related to weld quality. The nonlinear and largely coupled relationships between indirect and direct welding parameters are the major problem in welding process control.
Fig. 24- Weld pool oscillation frequency versus pool width for partially and fully penetrated pool [4].
Fig. 25- Illustration of the effect of weld pool constraint on pool oscillation modes [3].
The in-process NDE techniques, which extract direct information on weld quality, have no such disadvantage. In addition, in-process NDE techniques may be used to explore and improve the understanding of weld penetration and discontinuity formation, thus improving weld quality control.
Welding speed: 310 mm/min.
Arc voltage: 32 V
Rate inclination: 0° horizontal

Sensor output $V_s (V)$

Fig. 26- Correlation between arc light intensity and bottom bead width [9].
2.3 NONDESTRUCTIVE EVALUATION AS A TOOL FOR IN-PROCESS WELD QUALITY CONTROL

In-process NDE may be defined as the practice of using NDE techniques to gather information while the manufacturing process is still in progress. Radiography, ultrasonics, acoustic emission, electro-magnetics, liquid dye penetrant, and visual inspection are common NDE techniques applied for post-process weld quality inspection. The manufacturing process discussed here is arc welding. The major candidates among these NDE techniques for in-process NDE of arc welds are radiography and ultrasonics. In this section a short review of in-process ultrasonic and radiographic NDE is given to present the capabilities of in-process NDE techniques.

2.3.1 In-Process Ultrasonic NDE

Feasibility studies of monitoring the weld pool with ultrasonics were reported by Lott [54], Hardt and Katz [55], and Carson and Johnson [56]. Figure 27 shows the experimental system used for ultrasonic detection of the liquid-solid interfaces of the weld pool [54]. The ultrasonic measurements were made with the welding workpiece suspended in a conventional ultrasonic immersion test tank.
Fig. 27- Schematic diagram of ultrasonic detection of liquid-solid interface of weld pool [54].
The bottom surface of the workpiece was immersed in water to couple ultrasonic waves into the workpiece. The ultrasonic detection of the weld interfaces is based on the difference in acoustic impedance (depending on material density and sound velocity) between air, liquid metal, and solid metal. Hence, the locations of the weld interfaces are detectable by measuring the flight time of the ultrasonic pulses reflected from the interfaces.

Figure 28 shows ultrasonic A-scan results for a stationary weld spot using longitudinal sound waves [56]. Figure 28 (A) shows the reflected pulses measured before welding from the air-solid interface (top surface of sample) and from two side-drilled holes. The holes were placed in the weld sample as reference position markers. Figure 28 (B) shows the two reference reflectors and the reflectors seen during welding due to the formation of the weld pool and thermal gradients. The echoes from the holes come later in time, which corresponds to the decreased sound speed caused by the high temperatures in the workpiece. The echo signals from the solid-liquid interface, the top base metal surface, and the top pool surface are also shown in Figure 28 (B). The difference in ultrasonic transit time between the top of the weld and the bottom of the pool was found to be related to the weld pool depth.
Fig. 28- Ultrasonic A-scan of weld interfaces. (A) Before welding. (B) During welding [56].
In studies of the weld interface using non-contact ultrasonic transducers, Carson and Johnson [56] and Maxfield et al. [57] have reported the potential use of a laser sound source and an electromagnetic acoustic transducer (EMAT). The pulsed laser impinges on the weld, setting up stress waves that are transmitted through the workpiece and picked up by an EMAT receiver. The obvious advantage is that no contact between the ultrasonic transducer and the workpiece is required.

An ultrasonic technique, developed to detect weld discontinuities in partially completed welds, was reported in [56]. Figure 29 shows the A scans of flawed and well solidified weld metal. Analysis of the ultrasonic data shows that lack of fusion (incomplete sidewall penetration) and porosity can be detected by using pattern recognition techniques. In addition, ultrasonic reflections related to the shape of the solid-liquid interface were also studied.

In a study of underwater arc welding [58], the weld penetration has been successfully controlled by using in-process ultrasonic techniques. This is based on the relationship between the amplitude of the reflected wave from the weld bottom and the extent of the lack of penetration. A-scan ultrasonic information on weld penetration was obtained and fed back to adjust the welding current, thereby optimizing weld penetration.
Fig. 29- Ultrasonic A-scan of a good weld and weld with porosity and lack of penetration [56].
2.3.2 In-Process Radiographic NDE

Weld discontinuities, which contrast in either thickness or density with the surrounding metal, may be imaged by using radiographic techniques. A radiographic film (film radiography) or an X-ray sensitive electronic device (real-time radiography) can be used to detect the modulated X-ray field. The traditional film radiography has been widely used in industry for post-process weld flaw detection.

Using high-speed radiography (or flash radiography), which is based on impulse X-ray tubes and high-speed X-ray films [62], a few very interesting studies have been conducted on the fusion welding. The image is formed during the period of duration of the X-ray pulse. The use of flash radiography to study the mechanisms of metal drop formation on the consumable welding electrode was originally proposed by Becken [59]. Using an analogous method, Eichhorn [60,61] investigated the submerged arc process. Using the experimental system shown in Figure 30, Bryant [62] studied electron beam welding and the relationship between weld penetration and electron beam energy was found. Steinzel and Thomer [63] gave examples of the use of flash radiography for the study of the arc welding process. In a study of the arc welding process [74], a television X-ray image
Fig. 30- Schematic diagram of experimental setup for flash radiography during electron beam welding [62].
enhancement system was used to monitor consumable inert gas arc welding process on aluminum.

Flash radiography has not been widely used since the time of observation is very short and the time required for film processing is long. In addition, issues of the quality of radiographic images such as contrast sensitivity, resolution, and detectability have not been adequately resolved.

In recent years, the successful use of real-time radiography has become possible due to the development of high quality image intensifiers and digital image processing. An image intensifier coupled to a video camera, like the one used in our laboratory, is an example of an electronic receiver of real-time radiography data. This has resulted in high-quality images comparable to high-quality film radiography. The main industrial application of real-time radiography is in the post-process nondestructive evaluation of different structures. Real-time radiography has several advantages compared to film radiography as presented in Table 1. Basically, because of fast image acquisition and processing, real-time radiography is suitable for both in-process control and in-process inspection.

In this dissertation, real-time radiography has been implemented to provide in-process observation and control of
the arc welding process. Experimentally, the relationships between radiographic image brightness level and material thickness can be determined by taking the radiographic images of steel plates and shims of various thicknesses. Such a relationship may be used to reconstruct density and thickness from radiographic images.

For real-time application of NDE techniques, the acquisition and processing of information must be fast enough to extract useful information before any major change occurs in the welding process. This prohibits the use of some sophisticated and time consuming information processing techniques to improve the information quality. The change in material properties during welding has an effect on the interpretation of NDE information.

By using in-process NDE techniques, real-time detection of the direct welding parameters (weld discontinuities listed in Figure 19) is possible. With conventional welding process sensor, the detection of internal weld discontinuities is not possible.
Table 1: Comparison of film and real-time radiography.

<table>
<thead>
<tr>
<th></th>
<th>Film</th>
<th>Real-time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) information</td>
<td>about 30 min.</td>
<td>real-time</td>
</tr>
<tr>
<td>acquisition time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) capability of</td>
<td>yes (*)</td>
<td>yes</td>
</tr>
<tr>
<td>digital</td>
<td></td>
<td></td>
</tr>
<tr>
<td>information</td>
<td></td>
<td></td>
</tr>
<tr>
<td>processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) capability of</td>
<td>no</td>
<td>promising</td>
</tr>
<tr>
<td>real-time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>welding process</td>
<td>manual</td>
<td>promising</td>
</tr>
<tr>
<td>control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) capability of</td>
<td>manual</td>
<td>promising</td>
</tr>
<tr>
<td>real-time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>weld quality</td>
<td>film, chemicals</td>
<td>none</td>
</tr>
<tr>
<td>control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) consumable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) cost</td>
<td>labor-intensive</td>
<td>high capital</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cost</td>
</tr>
</tbody>
</table>

*: only for the film-camera system.
2.4 SUMMARY AND STATEMENT OF PROBLEMS

1. Conventional feedback weld penetration control is based on the relationship between the sensed physical quantity and weld penetration, which is indirect, and may be distorted by other factors. In addition, detection of weld discontinuities is not possible by any conventional welding process sensor.

2. The use of NDE techniques together with welding process control during welding is a new method for solving the problem of weld quality control. By integrating automated inspection with an automated welding process, inspection and manufacturing control may be combined.

3. In addition to their use in weld quality control, in-process NDE techniques together with other welding sensors may also be used to investigate the complicated arc welding process. Most past work, analytical or experimental, to study the arc welding process was approached either from the welding arc or the molten pool, resulting in a lack of proper explanation of their mutual interactions.

4. The arc plasma force, which acts on the molten pool, is one of several important factors which affect the arc-pool interactions. The welding arc force has been directly measured by several authors. Due to experimental difficulties, and because the measured values are possibly
apparatus dependent, there are significant differences among the data published by different authors, thereby making the use of the published data difficult.
CHAPTER III
EXPERIMENTAL CONCEPT

The objective of this chapter is to introduce the new concept of in-process weld quality control by using the radiographic NDE method and to discuss possible implementations. The general idea of using the capability of real-time radiography and other welding sensors to study the complex relationships between welding conditions, welding arc force, pool formation, weld formation, and weld discontinuity formation is described.

3.1 GENERAL CONCEPT

Penetrating radiography is one of several methods to obtain radiographic images. It is based on the attenuation of X-rays penetrating through a material, so it can be used to collect information on material thickness and density.

A schematic of the experimental setup for real-time radiographic monitoring of the arc welding process is shown in Figure 31. The X-radiation is parallel or at small angles to the welding torch. As shown in Figure 31, the X-ray tube
Fig. 31- Schematic of experimental vertical setup for real time radiographic observation of welding process.
was mounted above the image intensifier and below the welding piece.

An example of a frozen image (one frame) from a sequence of real-time radiographic images taken during submerged-arc welding is shown in Figure 32. The image is represented in positive form opposite to a film image. Images of the base metal, weld, molten pool, electrode, and welding torch are seen. The weld joint and the pool were covered by the granular welding flux and by the molten flux (slag). However, the flux affects an image only slightly because of its low density. The center dark region in the image is the weld. The upper part of this region corresponds to a weld with complete penetration. The lower part corresponds to a weld with insufficient penetration which is seen as a long light strip along the joint. The lower dark area with the semicircular shape is the welding gun; the welding electrode can also be seen. In front of the welding gun is the molten pool and the joint gap, which is a white area. The surrounding gray area of the weld is the base metal. The radiographic images were digitized in real time at 30 frames/sec.

Based on radiographic information on the pool, weld penetration, and location of welding wire and joint gap, welding process control, weld seam tracking, and weld quality control can be integrated together which are the
Fig. 32- Real-time radiographic image of submerged-arc welding where welding electrode, torch, joint gap, complete weld penetration, and lack of penetration can be seen.
basic requirements of weld quality control. The concept of integrated process and quality control using in-process NDE techniques is shown in Figure 33. The basic approach is shown in Figure 34. One image receiver can be used to monitor all the features shown in Figure 32.

3.2 SENSING AND CONTROL OF WELDING PROCESS

Sensed information on the welding process, which is related to weld quality, can be used in the feedback loop to control the welding process through adjustment of the welding parameters. Since the welding process has complicated nonlinear dynamics, a knowledge of the process is crucial to adequate measurement.

The arc-pool interaction involves electromagnetic and arc jet-liquid metal interactions and depends on the mutual interaction between the distribution of current density and heat flux and the shape of the depressed pool surface. Thus this interaction has the major effect on weld formation. Welding parameters such as arc current, voltage, and welding speed are related to weld formation through their effects on arc current density distribution, arc force, metal melting, pool depression, pool convection, and material properties.

Figure 35 is illustrates the interaction between the plasma jet and the weld pool. A bead-on-plate weld with a
**PROCESS = WELDING PROCESS**

**NDE = RADIOGRAPHY**

Fig. 33- Schematic illustration of in-process nondestructive evaluation (NDE) of weld.
Fig. 34- Experimental arrangement for integrated in-process welding process and weld quality control.
Fig. 35- Schematic illustration of plasma jet interaction with weld pool.
non-consumable electrode is shown. Due partly to the arc pressure on the molten pool, the pool is depressed during welding. "D" is the depression depth and "W" is the depression width. As the welding current increases, the depressed pool surface becomes deeper and wider because of the increase of the arc force. The position of the liquid-solid interface, which is related to the pool depression, partly determines weld penetration. A current level above 200 A is used here in order to create a depressed pool surface.

Heat input to the weld pool in arc welding occurs partially through heat transfer from the arc plasma and partially through Joule heating of the pool by the welding current [64]. Both of these effects depend significantly on the pool surface profile since this affects the arc plasma and current density distributions. On the other hand, the shape of the weld pool surface depends on the forces acting on the pool. Therefore, the problem of arc-pool interaction is strongly nonlinear.

Figure 36 shows the complex sequential relationships between the welding conditions, the arc force, the pool formation, and the weld formation. Among these, the welding arc and the pool formation are the core operations and interact with each other in a complicated manner. Formation of weld discontinuities, like tunnel pores and porosity, is
Fig. 36- Block diagram shows relations between welding conditions, force-pool interaction, and weld formation.
closely related to the arc-pool interactions. The stability of a deeply depressed pool surface depends partly on the plasma arc reaching the bottom of the depressed pool surface to maintain a stable surface. Convection in the pool is another factor which may cause instability of the depressed pool surface. Real-time radiographic information on the molten weld pool is available which may be used to reconstruct the depressed pool surface.

A complete analytical solution of the arc-pool interaction is not available at the present time. Suggested in the present work, Equation 6 is only a simplified expression and is useful to explain some aspects of the complicated arc-pool relation. Basically Equation 6 expresses the balance of different pressures acting on the pool surface caused by the arc plasma, electromagnetic, gravitational and surface tension forces, and the effect of convection in the pool (the Bernoulli-type force). For a consumable electrode arc welding process, like gas-metal-arc welding and others, the impinging metal is another component of the force from the welding arc, which affects the formation of the depressed pool surface.

\[ \text{ARC PLASMA PRESSURE} + \text{ELECTROMAGNETIC PRESSURE} = \rho gf(x,y) + \gamma (T)K(K_1,K_2) + \Psi (V,H) \] (6)

where

\[ x \text{ and } y \text{ are the coordinates with the } x \text{ in the} \]
cross-weld direction and y in the along-weld direction.

\( f(x,y) \) is the height of pool depression.

\( \varrho \) is density.

\( g \) is gravity.

\( \gamma \) is surface tension.

\( \kappa_1, \kappa_2 \) are the two principal curvatures of the pool surface.

\( T \) is the pool surface temperature.

\( \Psi \) is the Bernoulli-type force.

\( V \) is the velocity of pool convection.

\( H \) is the depth of the pool.

In this dissertation, based on information on the depressed pool surface and arc force measurements, the relationship between welding current, arc force, pool depression, and weld penetration were experimentally investigated, which provided the required information for weld quality control.

In-process NDE can provide process and quality information. In addition, in-process information obtained from the welding process may be utilized to analyze the process further and to provide insight into the process for future use as shown in Figure 33.
3.3 WELD QUALITY CONTROL

Direct weld quality control based on real-time information from the weld and the weld pool is illustrated in Figure 37. Figure 37 shows all of the welding features of the radiographic images, including the electrode, the welding torch, the molten pool, and the weld. For weld quality control, two image windows are made; one contains information on the solidified weld and one on the weld pool and the joint. One basic approach to feedback weld quality control is presented in Figure 38. Based on information on the pool and the weld, control of the welding process and the weld quality can be integrated together.

In the first approach to automatic weld quality control, an early detection of the depth of weld penetration is performed based on direct information on weld penetration obtained at some distance behind the weld pool. Automatic adjustment of the welding current may be made to obtain complete penetration. The contrast sensitivity and resolution of real-time radiography are critical factors in the detection of a small lack of penetration.

The second approach to weld quality control is based on the use of radiographic information on pool depression. For this purpose, investigation of the relationship between pool depression geometry and welding current is needed. Welding
Fig. 37—Schematic illustration of the windowing of radiographic image for the integrated welding process and weld quality control.
Fig. 38—Block diagram showing the approach of feedback welding process and weld quality control.
conditions may be automatically adjusted during weld quality control to maintain full weld penetration by comparing the measured depressed pool depth and width with threshold levels. The decisions made on weld penetration are sensitive to pool dynamics.

The third approach is integrated weld quality control using radiographic information on both the pool and the weld. The cycling rate of the decision process is expected to be critical, because more information must be processed during welding than the previous two approaches.
CHAPTER IV

EXPERIMENTAL SYSTEM FOR IN-PROCESS WELD QUALITY CONTROL AND EVALUATION OF ITS PERFORMANCE

The objective of this chapter is to evaluate the effect of the radiographic parameters on the quality of radiographic images from the viewpoint of revealing pool depression, weld penetration, and weld discontinuities. Contrast sensitivity (minimum detectable thickness change of the sample), resolution (minimum distance at which two flaws may be seen separately) and detectability (size of the smallest flaw which can be detected) will be investigated. When these parameters are determined, it is possible to predict the minimum flaw size in the weld which is detectable by a given radiographic system. The results of this study are general in nature and the methods developed may be applied to any radiographic system.
4.1 EXPERIMENTAL APPARATUS AND PROCEDURE

The schematic diagram of the experimental system is shown in Figure 39. Real-time radiography is used here as a vision system, albeit "X-ray vision", to monitor the welding process. With the X-ray absorption of the material known, radiography is used for thickness measurements in the vicinity of the weld pool and solidified weld.

The real-time X-ray and welding units are integrated as a single setup in an exposure room. Photograph of the experimental arrangement in the exposure room is shown in Figure 40. The radiographic system consists of exchangeable 160 KV and 300 KV X-ray sources and a 7-inch (178 mm) diameter Machlett Lab Image Intensifier. The X-ray sources and the image intensifier have remote control x-y lead shutters to reduce the effect of scattered radiation on the image. The welding torch and workpiece are placed between the X-ray source and the image intensifier in a vertical position. The welding part is mounted and moving on a 5-axis manipulator. The X-ray tube may be translated by the independent linear mechanical positioner. Both X-ray tube and image intensifier can be tilted and aligned relative to the welding part at the required angle of observation.

The welding power supply, manipulator and X-ray source are remotely controlled from the control room. A TFI Gemini
Fig. 39- Schematic diagram of the experimental system for weld quality control.
Fig. 40— Experimental setup showing the 160 KV X-ray unit (top), image intensifier (bottom) and welding apparatus.
II control unit is used for the 160 KV ceramic tube and a Phillips control unit is used for the 300 KV tube. An IBM-AT computer with analog-to-digital (A/D) and digital-to-analog (D/A) boards was used to control the welding power supply.

The radiographic image from the output of the image intensifier is picked up by a Vidicon television camera for observation and recording at the rate of 30 frames per second. Simultaneously, the television image is fed to the imaging board on an IBM-AT compatible computer. It is used for image enhancement and for extraction of quantitative information on weld pool and weld quality. During welding, current and voltage were measured and radiographic images were recorded.

The imaging system consists of two data translation boards, DT-2851 and DT-2858. DT-2851 is a high-resolution frame grabber and has two image buffers, each with 256 KB memory. DT-2858 is a high-speed frame processor. Both boards are linked by an internal high-speed bus and connected to the IBM-AT bus which has a lower speed. A packet of programs written in the "C" computer language was developed to operate the frame grabber board, the image processor board, and the welding power source, do data logging, and to analyze images and make decisions.

The controllable radiographic conditions on the X-ray tube are tube voltage (KV), tube current (Ma), and
magnification. In this experiment, a thin lead plate 50 microns thick with sharp edges was used to obtain the edge spread function (ESF) where the effective system unsharpness also was measured. Relations between system unsharpness and geometric unsharpness and pixel size will be discussed. Spatial frequency response was calculated from the edge spread function and compared with the measured spatial frequency response by using a lead resolution pattern (made by Nuclear Assoc., Carle Place, N.Y.) with slots of different spatial frequencies ranging from 0.25 to 10 lp/mm (line pairs per mm).

Contrast sensitivity was measured using steel shims of different thicknesses placed on a 6.35 mm (1/4 inch) thick steel plate. Signal-to-noise (S/N) ratio was measured under different radiographic conditions.

Detectability was tested with a 6.35 mm thick steel plate bearing different steel slots made by pairs of shims, as shown in Figure 41. The shim thickness and spacing were varied. Detectability curves for steel were constructed experimentally and compared with the estimated detectability curve obtained from the effective system unsharpness and contrast sensitivity.
Fig. 41- Schematic of experimental sample for detectability measurements (calibrated steel shims and plate).
4.2 EVALUATION OF RADIOGRAPHIC SYSTEM

4.2.1 Measurement of Source Spot Size

The spot size of the radiation source is one of the important parameters of a radiographic system. It can affect the system unsharpness and limit the radiation intensity of the source. For the current 160 KV X-ray system, there are two choices of spot size: one large (3 mm) and one small (0.5 mm).

The "T hole" of a 2-2T steel penetrator [15] was used as a pin hole to measure and verify the spot size. The small pinhole, was placed between the X-ray source and the radiographic film. The X-ray tube was set up at a distance such that the pinhole was halfway between the X-ray tube and the film; hence the spot size can be directly read from the film. After processing the film, an unsharp dark spot was seen on the film. The effective large and small spot size of the X-ray tube were roughly measured and found close to those given in the X-ray tube specification. The system geometric unsharpness is directly related to the spot size, and thus the system resolution. The accuracy of this kind of technique, which was first used by Halmshaw [65] to measure the X-ray tube with mini (10^3 meter) focal spot size, is sensitive to the exposure and to the obtained film density.
4.2.2 Determination of Field-of-View Pixel Size

A "pixel" (picture element) is the basic element constructing digital images and is one of the important system specifications. System sharpness and resolution are affected by the pixel size. For a given optical aperture, the pixel size is a constant system parameter. Field-of-view (FOV) pixel size, depending on magnification, corresponds to different sizes of the imaging area. The FOV pixel size also depends on the parameters of the analog-to-digital converter and TV raster lines. When X-ray magnification equals one, the FOV pixel size is measured to be about 0.21x0.21 mm. In this work with the capacity of 8-bit per pixel, each pixel has a maximum of 256 gray levels.

4.2.3 Unsharpness, Spectrum Response, and Resolution

Unsharpness, spectrum response, and resolution are three different physical quantities describing one nature of the radiographic system, that is the minimum distance at which two flaws may be seen separately. This is the important capability of a radiographic system in revealing small weld discontinuity.

Radiographic system unsharpness is a combination of the effect of the individual unsharpness in radiographic channel
including geometric unsharpness, pixel size (only for digital images) and screen unsharpness [65,66]. Obviously, larger individual unsharpness will yield a larger system unsharpness value.

A thin lead plate 50 microns thick with sharp edges was used to measure the effective system unsharpness. Figure 42 shows a typical edge spread function obtained from the real-time radiographic system. An effective unsharpness is calculated at the (1-1/e) level (± 31.5 percent from the center of an edge spread function). The incorporation of this value gives good results in exponential fits of the real edge spread function. Table 2 presents the measured effective system unsharpness value and the calculated geometric unsharpness at different magnifications.
Fig. 42—Typical edge spread function (ESF) obtained from the experimental setup.
Table 2. Measured Unsharpness.

<table>
<thead>
<tr>
<th>M</th>
<th>$\Delta y$ (mm)</th>
<th>$\Delta z$ (mm)</th>
<th>$U_g$ (mm)</th>
<th>$U$ (mm)</th>
<th>$U_s$ (mm)</th>
<th>$U$ (mm)</th>
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<tr>
<td>1</td>
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<td>0.22</td>
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<td>0.4</td>
<td>-0</td>
<td>0.4</td>
</tr>
<tr>
<td>1.5</td>
<td>0.14</td>
<td>0.15</td>
<td>1.4</td>
<td>0.5</td>
<td>0.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

where

- **FOV** - field of view.
- **M** - magnification.
- **$U_g$** - calculated geometric unsharpness.
- **U** - measured effective system unsharpness.
- $\sim 0$ indicates negligible unsharpness.
For the calculated geometric unsharpness, $U_g$, the (full) unsharpness value was taken; in contrast, the effective unsharpness were used for measured values. The pixel size in terms of field of view (FOV) was the area of view corresponding to a digitized pixel.

For magnification equal to one, the geometric unsharpness was negligible for both the large and small X-ray source spots. In this case, the system unsharpness was limited by the image-intensifier unsharpness and the FOV pixel size. For higher magnification, the effect of geometric unsharpness, $U_g$, became stronger and the corresponding size of the FOV pixel became smaller. At a magnification of 1.5, the $U_g$ for the large focal spot was the dominating factor and resulted in a larger value of system unsharpness. For the small spot at a magnification of 1.5, $U_g$ is comparable to the pixel size and the overall unsharpness of the system will thus be relatively small.

To have a smaller system unsharpness value, each individual unsharpness, including $U_g$, FOV pixel size and screen unsharpness must be minimized. Usually, a balance between the geometric unsharpness and the FOV pixel size can be made by adjusting the magnification. The optimal system unsharpness is achieved when all individual unsharpness are of the same order.

Spectrum response, called modulated transfer function
(MTF) which is related to the edge spread function, is the spatial frequency-domain representation of the radiographic unsharpness. For a low pass device like a radiographic system, higher frequency detail can't effectively pass through the radiographic system, or its contrast is reduced due to unsharpness. In this work, modulated transfer function were calculated by taking the convolution integral \([67,68]\), from minus infinite to infinite, of the line spread function (the derivative of the edge spread function) with the harmonic function and normalized to the DC component (zero frequency), as expressed in Equation 7.

\[
MTF(f) = \frac{\int_{-\infty}^{\infty} L(x) e^{-jfx} dx}{\int_{-\infty}^{\infty} L(x) dx}
\]

where

- \(x\) is the coordinate in space.
- \(f\) is the spatial frequency.
- MTF is the modulated transfer function.
- \(L(x)\) is the line spread function, equal the derivative of the edge spread function.
- \(k\) is the space wave number.

The solid line shown in Figure 43 is the calculated result of the modulated transfer function. It can be seen that no decrease of the original signal amplitude (100 \%
Fig. 43—Experimental data for system frequency response. Solid line: calculated from ESF.
response) at the low frequency and the response starts to
decrease at a higher frequency, like a low pass filter. Data
points of the measured modulated transfer function are also
shown in Figure 43. It was made by using a lead pattern of
slots with different spatial frequencies and normalized to
the response of the slots with lower spatial frequency, 0.5
lp/mm in this case. The experimental data matched to the
calculated spectrum response very well as shown in Figure
43. The spectrum response is similar to that of a low pass
filter, with cutoff at 2.4 lp/mm which is the system
resolution. A smaller unsharpness value (sharper image) will
give better response and results a higher resolution.

In application of radiographic system, the amplitude of
output signal depends on the amplitude of input signal
multiplied by the modulated transfer function (Equation 8).
At high frequency the amplitude of the transfer function is
low, therefore detail with higher frequency can not be
effectively passed through the radiographic channel. It
becomes difficult to detect the output signal when its
amplitude is close the noise level of the radiographic
system.

\[ S_o(f) = S_i(f) \cdot MTF(f) \] (8)

where

\( S_o \) is the spectrum of the output signal.
\( S_i \) is the spectrum of the input signal.
MTF is the modulated transfer function.

f is the spatial frequency, lp/mm.

4.2.4 Signal-to-noise Ratio and Threshold Contrast Sensitivity

In addition to system resolution, the contrast sensitivity is the other major parameter of the radiographic system and especially important to the accuracy of thickness measurement, for example reconstruction of the depressed pool surface from radiographic images. Contrast sensitivity is determined by the minimal thickness decrement (Δh) of the part to be exposed which directly influences the smallest visible changes in the brightness (ΔB) of the screen. It can be calculated [69] as in Equation 9.

\[
\frac{\Delta h}{h} = \frac{(1+I_s/I_d)}{\mu \gamma h} \frac{\Delta B}{B} \tag{9}
\]

where

μ is the absorption in the material

I_s is the intensity of scattered radiation

I_d is the intensity of direct radiation

h is the thickness of the part

B is the brightness level on the TV screen corresponding to the given thickness of the sample, h
\( \gamma \) is the system gamma that characterizes the sensitivity of the image intensifier and TV system.

The threshold level of the brightness change \( \Delta B \) is determined by the noise level of the system hence the contrast sensitivity. Radiographic noise is mainly composed of two parts, quantum noise and noise from the radiographic imaging system (called device noise). Each possesses both spatial and temporal components. In this work, the statistical characteristics of noise are expressed by the mean value and the standard deviation of the brightness level. For a perfect radiographic channel, every pixel will have the same gray level and hence the standard deviation will be zero.

A small change in the sample thickness leads to a small change in screen brightness, \( \Delta B \). This change of brightness may be considered a signal since it carries useful information (an existing discontinuity changes the thickness of the sample). Such a discontinuity may be simulated by a shim with calibration thickness, \( \Delta h = t \). The mean value and the standard deviation are regarded as the signal level and the noise level, respectively. The signal level of a shim on a plate can be obtained as expressed in Equation 10.

\[
\frac{S}{N} = \frac{(p-s)}{\sigma} \quad (10)
\]
where

$S/N$ is the signal to noise ratio.

$p$ is the mean brightness of the background plate.

$s$ is the mean brightness of the background plate with shim.

$S (= p - s)$ is the brightness change due to shim (signal).

$\sigma$ is the standard deviation.

It is expected that maximum tube current would give the best $S/N$ ratio and hence the best minimum visible contrast sensitivity because the $S/N$ ratio is proportional to the square root of the number of incident photons [15]. The highest $S/N$ ratio for a 2 percent shim on 6.35 mm thick (0.25 inch) steel plate was obtained using 110 KV and 25 Ma. The 2 percent shim was selected to find the optimal current because it can easily be observed by the operator. Averaging of 20 frames was used to reduce the noise level.

Using the X-ray tube voltage and current selected, the signal and noise level for several shims were obtained. The data are presented in Table 3. For a small range of shim thickness change, the ratio of the brightness variation, $\Delta B$, to the shim thickness, $t$, is approximately constant (see last column in Table 3), where

$$t/\Delta B = \text{constant} = 0.012$$
If one takes the threshold level for visible brightness, $\Delta B$, equal to $2\sigma$, then the corresponding threshold shim thickness may be found as follows:

$$\frac{t'}{2\sigma} = \frac{t}{\Delta B} = 0.012$$

This gives the value 1 percent for contrast sensitivity, $t'/h$, where $h$ is the thickness of the background plate.

The shim threshold thickness, $t'$, was also found directly by decreasing the shim thickness up to a value at which it became invisible on the screen to the human eye. The 1 percent value was confirmed by such direct measurements.

The contrast sensitivity of the system was measured to be 1.5 percent. It becomes about 4 percent for in-process radiography of submerged arc welds due to the effect of flux and slag, which have high structural inhomogeneity and increase the noise in the image. For this case, the accuracy of the radiographic measurement of thickness is about 0.25 mm (0.01 inch) based on 4 percent contrast sensitivity on a 6.35 mm (0.25 inch) thick steel plate.
Table 3. Measured signal-to-noise ratio.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>t/h %</th>
<th>σ Levels</th>
<th>ΔB Levels</th>
<th>t/ΔB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025 mm</td>
<td>0.4</td>
<td>2.3</td>
<td>2</td>
<td>0.013</td>
</tr>
<tr>
<td>0.076 mm</td>
<td>1.2</td>
<td>2.3</td>
<td>7</td>
<td>0.01</td>
</tr>
<tr>
<td>0.127 mm</td>
<td>2</td>
<td>2.5</td>
<td>10</td>
<td>0.013</td>
</tr>
</tbody>
</table>
4.3 COMPUTER SIMULATION OF RADIOGRAPHIC IMAGES OF WELD WITH DISCONTINUITIES

In this section radiographic images of the weld are simulated to study the important effect of X-ray system parameters on the radiographic projection. The effect of radiographic system unsharpness on radiographic projection as discussed above was simulated. As an example, weld face reinforcement and lack of penetration (a discontinuity) were approximated by ellipses. The simulated and the experimentally obtained brightness profile were compared.

Figure 44 (A) shows a segment of an ellipse which is located at the origin of coordinates and Figure 44 (B) shows the schematics of a weld with lack of penetration. Equation 11 is the equation of an ellipse at the origin of coordinates. A and B are two semi-axes of the ellipse. Also shown in Figure 44 is the (s,t) coordinate system, with the s coordinate parallel to the x-ray beam, which represents the radiographic system.

\[
\frac{x^2}{A^2} + \frac{y^2}{B^2} = 1 \quad (11)
\]

where

x and y are the object coordinates.

A and B are the two semi-axes of the ellipse.
Fig. 44— Computer simulation of radiographic images. (A) Schematic of ellipse segment in (x,y) and (t,s) coordinates. (B) Modelling of weld shape with face reinforcement and lack of penetration.
The projection of an elliptical segment, which is the shaded area in Figure 44 (A), was calculated. A weld face reinforcement and a lack of penetration were approximated by an elliptical segment as shown in Figure 44 (B). In Figure 44 (B) \( S_1(t) \) is an ellipse and \( L_1(t) \) an line in the \((t,s)\) coordinate. The projection of the elliptical segment can be obtained by subtracting \( L_1(t) \) from \( S_1(t) \). In order to obtain radiographic projections at an arbitrary X-ray beam angle \( \theta \), coordinate transformation, from \((x,y)\) to \((t,s)\) coordinates is applied as expressed in Equation 12 and 13.

\[
S_1(t) = \frac{-t(A^2-B^2)\sin(\theta)\cos(\theta) + AB\sqrt{a^2-t^2}}{a^2} \quad (12)
\]

\[
L_1(t) = \frac{d-t\sin(\theta)}{\cos(\theta)} \quad (13)
\]

where

- \( \theta \) is the transformation angle.
- \( d \) is the distance from the origin to the line.
- \( S_1 \) is the function of the ellipse in the \((t,s)\) coordinate.
- \( L_1 \) is the function of the line in the \((t,s)\) coordinate.
- \( a^2 = B^2 \sin^2(\theta) + A^2 \cos^2(\theta) \).

Assuming a linear radiographic system, the radiographic attenuation of each part of the weld was individually calculated and superposed (weld reinforcement) or subtracted
(lack of penetration). Proper integration limits for each area were required as shown in Figure 44 (B) and Equation 14. The first term on the right hand side of Equation 14 is the projection for the base metal, the second term that for the face reinforcement, and the third term that for the lack of penetration (note the minus sign of this term).

\[ S_s(t) = (L_1 - L_2) + \left( S_1 - L_1 \right) t_1 - \left( S_2 - L_2 \right) t_2 \]  \hspace{1cm} (14)

where

- \( S_s \) is the superposed projection of the weld.
- \( S_1 \) is the shape of the face reinforcement.
- \( S_2 \) is the shape of the lack of penetration.
- \( L_1 \) is the function of the plate top surface.
- \( L_2 \) is the function of the plate bottom surface.

The effect of system unsharpness on radiographic projections was modelled by considering the effect of geometric unsharpness, screen unsharpness, and pixel size. For a finite spot size, geometric unsharpness depends on the spot size, the source-to-object distance, the source-to-receiver distance, and the distance from the center of the beam. In this experiment, the source-to-object distance was about 1.8 m and the object-to-receiver distance was less than a few mm. The calculated conic beam angle was smaller than one degree. Therefore the effect of conic beam can be
The screen unsharpness was modelled as a point spread function (PSF) having a fraction of light ($p$) scattered and the rest ($1-p$) non-scattered as expressed in Equation 15 [70]. $k$ is the mean propagation distance of scattered light in the screen. The output projection from the screen is calculated by convolving the diffusion function with the original projection as expressed in Equation 16. In this work $p = 0.28$ and $k = 2.7$ cm were used. The effect of image pixel size on the radiographic image was obtained by accumulating and averaging the incoming photons in an area of the pixel size.

\[ h(r) = (1-p) \frac{\delta(r)}{r} + \frac{p}{2kr} e^{-r/k} \quad (15) \]

\[ S_w(t) = S_g(t) * h(t) \quad (16) \]

where

- $h(r)$ is the point spread function of the screen.
- $r$ is the radial distance.
- $p$ is the fraction of light scattered.
- $k$ is the mean propagation distance of the scattered light.
- $\delta(r)$ is the delta function.
- $*$ is the convolution operator.
- $S_w$ is the projection of the weld.
The simulated radiographic profile of the weld with lack of penetration together with the experimental brightness profile is shown in Figure 45. In Figure 45 (A), overlaid ellipses which match the outline of the weld reinforcement and lack of penetration can be seen. The top ellipse has a horizontal radius $8.2 \text{ mm}$ and a vertical radius $4.6 \text{ mm}$. The width of face reinforcement is about $15.4 \text{ mm}$. The bottom ellipse has a horizontal radius $1.3 \text{ mm}$ and a vertical radius $2.4 \text{ mm}$. The width of lack of penetration is about $2.2 \text{ mm}$.

Figure 45 (B) shows the simulated (solid line) and experimentally obtained (solid dots) projections. It can be seen that they match well. At point A in Figure 45 (B) is the profile of lack of penetration. The round-off of the simulated projection at weld edges is due to the effect of radiographic unsharpness. The slight mismatch of the right half projections was possibly due to the misalignment of the X-ray beam and a slightly lower brightness was obtained from experiment.
Fig. 45—Results of computer simulation (A) Weld cross-section with overlaid ellipses shown. (B) Comparison of measured and calculated radiographic profile of weld with lack of penetration.
4.4 DETERMINATION OF SYSTEM DETECTABILITY

Detectability may be defined as the size of the smallest visible discontinuity which is important to the detection of small weld discontinuity as simulated above. In particular, this size may be less than the pixel size. In this case, only the existence of the discontinuity may be determined from the image while its actual size cannot be found. Detectability depends not only on the size of the flaw in the plane of the image but also on its thickness. Therefore, detectability and contrast are interrelated.

Contrast sensitivity as discussed in the previous section is a radiographic characteristic for a large-area flaw (for example a shim or a large weld reinforcement). For a small flaw the effect of unsharpness as discussed will reduce the contrast sensitivity, as illustrated in Figure 46, where it is shown that the contrast of a narrow slot was decreased due to system unsharpness (so-called unsharpness-induced contrast reduction [71-73]). In Figure 46, the edge spread function is drawn as a straight line for simplicity.

The dependence of the minimal visible size in an image plane of the flaw on the discontinuity contrast is called the detectability curve (the discontinuity contrast is defined below). The detectability curve of the long, narrow slot can be derived theoretically. As seen from Figure 46
Unsharpness-induced reduction of contrast for slot

Fig. 46- Effect of unsharpness on edge image and unsharpness-induced reduction of contrast for slot.
the brightness reduction due to unsharpness is expressed in Equation 17.

\[
\frac{\Delta B}{B_o} = \frac{\Delta y}{U} \quad (17)
\]

where \( \Delta y \) is gap width and all other values are clear from Figure 46. Therefore, the actual contrast of the flaw, \( C \), will be less than the expected value \( C_0 = \Delta h/h \) for a given flaw thickness \( \Delta h \) as expressed in Equation 18.

\[
C = C_0 \frac{\Delta y}{U} \quad (18)
\]

To see a small flaw, the actual contrast, \( C \), has to be equal to or greater than the threshold contrast sensitivity, \( C^* \), as expressed in Equation 19.

\[
C = \frac{\Delta h}{h} \frac{\Delta y}{U} \geq \frac{\Delta h^*}{h} = \text{constant} \quad (19)
\]

where

- \( \Delta y \) - width of gap
- \( \Delta h/h \) - expected contrast
- \( \Delta h^*/h \) - threshold contrast (contrast sensitivity)
- \( U \) - system unsharpness.

It is necessary to distinguish clearly between contrast sensitivity, \( C^* \), (threshold contrast level corresponding to the minimal thickness of a large-area flaw which is still visible on a screen) and contrast of the given flaw, \( C \), determined by Equation 18. Using the equals sign, the
threshold detectability curve can be drawn on a contrast-detail diagram taking the experimentally measured threshold contrast sensitivity, $\Delta h'/h$, as parameter $\Delta y$ against $\Delta h/h$.

Detectability was experimentally measured and compared with the estimated detectability curve (Figure 47). The measurements were taken using calibrated shims (Figure 41). For a given penetrator thickness, $\Delta h/h$, the width of the gap between shims was reduced up to the point at which the gap became invisible on the image. The width of the narrowest visible gap is shown in Figure 47 as a solid point. Invisible gaps are shown by open circles, apparent gaps by solid circles and intermediate cases by half solid circles. The detectability curve is the threshold contrast sensitivity for discontinuities of different sizes. Above the detectability curve is the visible region; below it is the nonvisible region.

When the detail is larger than the system unsharpness, there is no contrast reduction. This is the point on the right end of the detectability curve. Physically, when the detail is smaller than the system unsharpness value, higher object contrast is needed for its observation on an image. This explains why the detectability curve for small detail rises to higher object contrast.

Using a detectability curve, evaluation of the quality of radiographic images is much more precise than using a
Fig. 47- Detectability curve for narrow slot. Theoretical curve is represented by the solid line.
penetrameter. The detectability curve gives the contrast sensitivity for different detail sizes and different thicknesses. The penetrameter represents only one point on this curve.

4.5 SUMMARY

(1) Important radiographic parameters, contrast sensitivity, resolution, and detectability have been investigated. When these parameters are determined, it has been shown that it is possible to predict the minimum flaw size in the weld which is detectable by a given radiographic system. The results of this study are general in nature and the methods developed may be applied to any radiographic system.

(2) For a feature of larger size, like weld reinforcement and pool depression, contrast sensitivity is more important than system resolution in the reconstruction of the thickness from radiographic images. Detectability of lack of weld penetration with large width also depends on the system contrast sensitivity. Contrast sensitivity of real-time radiography has been measured about 2% for normal case and about 4% for submerged arc weld due to the granular welding flux used for welding purpose.

(3) For an object of small feature, like crack, its
detection depends more on system resolution than contrast sensitivity. Contrast-detail-detectability (CDD) has been provided for this purpose. For a joint gap width greater than the system unsharpness, the effect of system resolution on its detection may be avoided.

(4) It is noted in the detection of the existence of small discontinuity that human visual perception may be capable to detect smaller discontinuity than the pixel size of a machine vision.
5.1 INTRODUCTION

In this chapter a radiographic method for real-time measurement of weld pool surface geometry with simultaneous recording of the arc plasma force acting on the pool will be described.

Quantitative measurements of the weld pool surface and the arc plasma force, which are related to welding conditions and determine weld formation, are fundamental to arc welding and can be used to improve our understanding of the basics of weld pool formation. The welding environment creates difficulties in making such measurements resulting in the absence of a proper method to monitor the depressed pool surface. As a result, most quantitative experimental studies of the arc plasma-pool interaction have been restricted to a flat pool surface, while in reality the pool surface is clearly depressed at high currents.

Several recent theoretical studies have also
demonstrated the importance of pool surface depression to the arc plasma-pool interaction \([24,42,53]\). In a computer model of weld penetration \([42]\), pool depression was found to be a major factor related to weld penetration. The distribution of the welding arc current density, which is a primary welding parameter, was calculated by Choo et al. \([24]\) and found to be significantly affected by the shape of the depressed pool surface. But there is also the inverse effect of the plasma column shape and the current distribution on the geometry of the pool surface. Thus the problem of arc plasma-weld pool interaction has nonlinear boundary conditions. Virtually all other physical quantities associated with the welding arc and the molten pool are affected by the current density distribution. Obviously, convection in the pool is also influenced by the shape of the weld pool surface.

The shape of the weld pool surface is determined by the balance of forces which act on the molten pool. These include arc plasma, electromagnetic, surface tension and hydrodynamic forces. The welding arc force has been directly measured by several authors \([39-41]\). Due to experimental difficulties and since the measured values are possibly apparatus dependent, there are significant differences among the data published by different authors. This is due partially to the fact that the arc plasma force is only
about 30% of total force, depending on the experimental arrangement. It is necessary to subtract the electromagnetic force from the total force to obtain the arc plasma force, thus increasing the error in its estimation.

The objective of this work was to develop a real-time technique for simultaneous measurement of weld pool depression and arc force acting on the pool. For this purpose a balanced force measurement device combined with a real-time radiographic system and other welding sensors has been developed. All measured parameters including radiographic images are digitized, computer analyzed, and processed in real time. An improved technique for arc force measurement and a technique for reconstruction of weld pool depression will be described below. We will also discuss the effect of material density and thermal expansion on radiographic measurement of pool depression. The work reported here provides a foundation for studying the relationship between the arc plasma force and weld pool depression and stability. The results of measurements using these techniques will be presented in the next chapter.

5.2 EXPERIMENTAL CONCEPT

In this section, the general concept of using real-time radiography with an arc force sensor for real-time
measurement of the welding arc and weld pool interaction will be discussed. Because of the difference in material thickness and density, the depressed pool surface can be measured by radiography. Radiography is based on the attenuation of X-rays penetrating a material to image the distribution of material thickness and density.

As an example one frame from a sequence of radiographic images of the molten pool taken during stationary GTA welding is shown in Figure 48. The welding torch is seen as a dark semicircle in the bottom of the image and the tip of the tungsten electrode is seen as a dark spot in front of the torch. The circular white area in front of the tungsten electrode is a depressed weld pool. The image is positive, so thinner sections of the depressed weld pool (reduced thickness of the material) are represented by lighter areas. The dark circle surrounding the white area corresponds to increased thickness and shows that the base metal is melted and pushed away due to the plasma jet forming a humped region on the periphery of the pool as shown in Figure 48. The gray area surrounding the pool is the base metal. When the welding current is high enough, melting of the base metal is intense and the light area becomes larger and lighter.

Real-time radiographic information on the molten weld pool is available in digital form and is used to reconstruct
Fig. 48 - An example of a frame from a sequence of radiographic images of the molten pool taken during stationary GTA welding.
the depressed pool surface. Based on measurement of the depressed pool surface and the arc force, the relation between welding current, arc force, pool depression, and weld penetration will be established here and in the following chapter which will provide the required information for weld quality control.

5.3 EXPERIMENTAL APPARATUS

5.3.1 Description of the Apparatus

This section describes the experimental apparatus for simultaneous measurement of the weld pool depression by radiography and the arc force by a balanced force measurement device. Figure 49 shows a schematic of the experimental apparatus. A force measurement apparatus using a digital scale was built for arc force measurement. The real-time radiographic apparatus is at the left and the force sensor is at the right. To eliminate the effect of X-ray beam shielding by the force measuring cell the apparatus was designed in the form of a balance, where the cell was on the opposite side from the X-ray beam.

The real-time radiographic imaging apparatus consists of x-ray source, image intensifier and camera, image processing board and digital computer. The X-ray tube, shown
Fig. 49- Schematic of the experimental apparatus for simultaneous measurement of arc force and pool depression.
on the top, produces collimated radiation which penetrates the material. The modulated X-ray field is acquired using an image intensifier and a video camera at 30 frames per second. The image is digitized by the image processing board and processed by computer. X-ray shutters are used to reduce radiographic noise.

The arc force measurement apparatus consists of force sensor (a digital scale), balance beam, pivot, bearing agate, and pivot supporters, as shown in Figure 49 for the measurement of both the arc force and electromagnetic force and in Figure 50 for the measurement of electromagnetic force alone (no welding arc). The workpiece was placed at one end of the beam and the balance weight at the other end to prevent scale overload. Figure 51 shows the area around the pivot in detail. A photograph of the experimental arrangement is shown in Figure 52; the digital scale may be seen at the left and the welding torches are at the right. The scale was a Toledo Scale Co. 8581 digital scale with a capacity of 600 g x 0.01 g.

The balance beam is made of a hollow aluminum square bar about one meter long. Aluminum is used here because it is light and non-magnetic. The pivot is made of stainless steel with a sharp knife edge at one end, the other end being circular (Figure 51). The pivot is mounted on the balance beam approximately in the middle. The balance beam
Fig. 50- Schematic of the arrangement for reference measurements (electromagnetic force measurement).
Fig. 51 - Detailed diagram of the balanced beam support for the force measurement device.
Fig. 52- Photograph of the balanced force measurement device. Digital scale is at left and welding torches are at right.
with the sharp knife edge of the pivot sits on the bearing agate which is a hard semiprecious stone. The sharp edge used here is to reduce the friction force between the pivot and the pivot supporter.

5.3.2 Processing of Data for Force Measurement

The balance weight, which is positioned on the right side of the balance beam (Figure 49), was selected to produce a positive net force on the digital scale, about 50 to 100 grams. During welding the net force measured by the digital scale decreases because of the arc and electromagnetic forces which act on the left side of the balance beam. When presenting the data, we plot in most cases the actual welding force acting on the left end of the balance beam, or in some cases inverted values shown by the scale (instead of negative force changes corresponded positive changes are shown).

The scale was set to continuous output data mode. The force readout from the scale is fed to the computer in digital format through the RS232 serial port (Figure 49). Each set of data consists of 6 bytes. A 6-digit hexadecimal value is obtained from the least significant nibble of each byte. A computer program converts the hexadecimal value to a decimal value which corresponds to the actual force. The
force information obtained in test mode has a higher resolution than the force obtained in the normal mode. In the normal mode, the scale precision is 0.01 gram. The force data acquisition rate on the scale is about 4 to 5 data points per second, limited by the internal averaging mechanism built into the scale. Including the time of taking radiographic image frames, the overall data acquisition rate is about 2 times per second.

5.3.3 Test of the Balanced Force Measurement Apparatus

Zeroing error, accuracy, and linearity of the balanced force measurement device are critical to force measurement. Before welding these were tested by using combinations of different precision weights placed at the same location where a welding arc would later be positioned on the test plate.

The accuracy and the zeroing error of the balanced force measurement device were determined to be within 0.05 grams. The results are shown in Figure 53 and 54. This is better accuracy than previously reported in the literature on arc force measurement [39,41]. The deviation from linearity of the apparatus was less than 0.01 gram.
Fig. 53- Summary of the results for accuracy determination of the balanced force measurement device.
Fig. 54– Zeroing error of the balanced force measuring device (found to be within 0.05 grams).
5.3.4 Floating Liquid Gallium Contact

Because the measured arc force is expected to be very small and the electromagnetic interaction due to current flow through workpiece strong, the effect of the mechanical contact of the electric cables connecting to the test sample must be minimized. A floating electric contact using liquid gallium was used to connect the cable from the positive terminal of the welding power source to the test plate, as shown in Figures 49 and 50. For the non-welding case (reference measurement), an additional liquid gallium contact was used at the same location where a welding arc would later be positioned. By retaining the same experimental configuration, the arc force may be obtained by subtracting the electromagnetic force.

During welding the welding current was conducted from the positive terminal of the power source through the electric cable, the liquid gallium pool, the test plate and the welding arc, then back to the negative terminal of the welding power source (Figure 49). Thus on the test plate both electrical contacts have mechanical floating with the workpiece and the current flows through the welding electrode, arc plasma column, workpiece, liquid gallium terminal, and ground.

This arrangement for welding force measurement has
advantages over those previously reported in the literature: in [39], the ground cable was made of a flexible, flat-woven Cu cable; in [41], the ground cable was held in place by several springs.

For reference measurements the experimental arrangement shown in Figure 50 was used. Here both contacts on the test plate were made using the liquid gallium. Substitution of the arc-plasma by a liquid gallium contact has been suggested previously in reference [40]. The purpose of this reference test is to measure the electromagnetic force without the effect of the arc plasma.

Liquid gallium has a melting temperature 30° C and a boiling temperature 2403° C [75]. The large temperature range of gallium in the liquid state makes gallium a good liquid electric conductor in a high temperature environment. Gallium ordinarily is not toxic and no special precautions are required. The gallium holder is a hollow cylinder thus the liquid gallium contacts the test plate directly. The gallium holder was made of ceramic material about 10 mm in height and 12 mm in diameter. The electrode-to-workpiece distance was 4 mm and the electrode diameter 3.178 mm.

The effect of the interfacial force between the electrode and the liquid gallium must also be considered. An interface force may exist on the positive electrode for the welding case and on both the positive and negative
electrodes for the non-welding case. Figure 55 shows the difference of measured force between that read while the electrode is in the liquid gallium and that read while the electrode is free. The difference is about 1.12 gram which is of the same order as the arc plasma force. This is important to an accurate measurement of the arc force, and has not previously been reported.

In this work the interface force was kept constant before and after welding to eliminate its effect on the force measurement. This was done by preventing the gallium from overheating by using a shorter time. During the arc force measurement, the absolute force measured before and immediately after welding was examined and found to be about the same which indicates that the effect of the interfacial force on the arc force measurement is negligible.

In addition to the interfacial force, the effect of change of the electrode position in the gallium pool was also tested. While the electrode was in the liquid gallium, the electrode was shaken to observe the effect on the force. The result is shown in Figure 56. The force difference is about 0.18 gram and the zeroing error is about 0.08 gram, both small compared to the arc force. In actual experiments of arc force measurement, the electrode was fixed and rigid.
Fig. 55- Change of measured force during removal of tungsten electrode from and insertion into the liquid gallium. The change of the force corresponds to the interfacial force between liquid gallium and electrode.
Fig. 56- Effect of electrode motion on interfacial force between electrode and liquid gallium. The force difference is about 0.18 gram and the zeroing error is about 0.08 gram.
5.4 EXPERIMENTAL PROCEDURE

The system described above combining the balanced force measurement device with the real-time radiographic apparatus, was used for simultaneous measurement of arc force and pool depression. To separate the arc plasma force and the electromagnetic force (existing during welding) two independent tests were made. One test was made with the welding arc (Figure 49); the other test was made with a liquid gallium contact replacing the arc (Figure 50). For both cases the electric contacts, arc or gallium, were well within the test plate (more than one inch from the edges) so that the uneven electromagnetic interaction at the plate edges could be minimized. In order to verify the measured arc force, tests were also performed at a different position on the test sample.

The stationary gas-tungsten-arc welding process was used for its simplicity in experimentation. The welding power source was a Miller Intelliweld 650 power source with a capacity of 100% duty cycle at 650 amps and 44 volts. The fluctuation of its output current was found to be within one ampere; thus its effect on the arc force measurement is negligible. After welding, the test plate was cut to measure the weld penetration which was compared to the pool surface depression obtained from radiographic images.
Two GTA welding torches were used, one for maintaining the welding arc and the other bridging the positive polarity to a pool of liquid gallium on the test plate (to be electrically connecting and mechanically floating). The first torch was a Heliarc HW-27 GTAW torch with a capacity of 100% duty cycle at 500 amps. The second torch was a Heliarc HW-18 GTAW torch with a capacity of 100% duty cycle at 300 amps. Because of the low capacity of the second electrode, a short electrode extension was used to prevent overheating which is critical to the maintenance of a constant interfacial force between liquid gallium and electrode. Both torches were water cooled. The arc was started by using steel wool between the electrode and the workpiece.

A 2% thorium tungsten electrode, 3.175 mm (1/8 inch) in diameter with electrode tip angle ground along the electrode to about 30 degrees with slight truncation at electrode tip was used. At 30 degree tip angle, the length of the ground area on the electrode is about 6 mm which was checked each time of preparing electrode. The electrode extension was set at about 57 mm and a torch angle of 70 degrees was selected. The unusual 57 mm long electrode extension was used to avoid shielding the radiographic image of the weld pool. A precise 4 mm electrode-to-workpiece distance was set by using a precision gauge. The 4 mm electrode-to-workpiece distance
was used to compare the welding force to that reported in other works [39-41].

Welding grade argon shielding gas was used with flow rate of about 60 CFH (cubic feet per hour). At 60 CFH, the force contribution of the shielding gas flow is small, less than 0.20 gram, compared to the total force. Reference measurements were also done with the argon flowing.

5.5 EXPERIMENTAL INVESTIGATION OF ARC FORCE

The welding arc plasma force is one of several factors important to pool formation and pool surface stability. The most important factor affecting the arc force is the welding current. The relation between arc force and current is discussed here.

5.5.1 Measurement of Arc Force

Figure 57 (A) shows the measured force of the precision weights, 20.00 grams. The measured force is within 0.01 gram of the precision weights. The scale takes about one second to reach a steady value. Figure 57 (B) shows a typical example of the forces measured at 350 A for the welding arc and non-arc cases. Both forces are shown in the figure for comparison. They reach steady values within 1.5 seconds. For
Fig. 57- Force measurements. (A) Time response of the device at weight change. (B) Measured force for arc welding and reference measurement versus time. Current is 350 A and is switched on at t=0. The difference between two measurements is the arc force.
the welding arc case the force was measured to be about 9.63 grams (about 8.70 grams for the non-arc case).

Because of the identical geometric experimental configuration, the distribution of the electromagnetic force is similar for both cases. Therefore, the arc plasma force could be obtained by subtracting the electromagnetic force from the total force measured. For the case shown in Figure 57 (B), the arc force is about 0.93 grams at 350 A.

During power-on, the second tungsten electrode (liquid gallium contact) gradually becomes hot due to resistance heating. The increase of electrode temperature affects the interfacial force between the tungsten electrode and the liquid gallium pool and is possibly characteristic of the electrode. A small change of the measured force, less than 0.20 gram, was found for a longer time of welding. A similar change of the interfacial force was also found by measuring directly on the scale which eliminates the possible effect of the balanced beam. In order to minimize electrode overheating and keep the interfacial force constant, a 3 second welding time was used to study the current-arc force relation. The results of these measurements are reported in the following section.

An additional effect is that alloying elements like thorium in the first tungsten electrode (used to maintain the arc) may be lost from the surface during welding, so
that the arc characteristics may change slightly. This is the reason for seasoning (welding with) the tungsten electrode several times before making the actual test [39]. Unfortunately during seasoning, the shape of the electrode tip changed. In the present study a newly ground tungsten electrode was used in each test to keep the electrode tip shape as constant as possible, and thus minimizing the effect of shape change on force measurement.

Before and after each experiment, the zeroing error of the balanced force measurement device was obtained. It was found to have average value less than 0.10 gram for both the welding arc and non-arc cases. This indicates the accuracy of the force measurement. For the cases shown in Figure 57 (B), the zeroing error was 0.046 gram for the welding case and 0.10 gram for the reference case.

The test plate was relatively large compared to the distance between the electrodes. In this way the welding current and electromagnetic field can be more uniformly distributed [80]. Therefore no arc blow was observed during welding due to the edge effect. During experimentation, no effect of the cable position on the force measurement was found. This was tested by varying the position of the cable at a distance of about half a meter away from the arc.
5.5.2 Relation Between Current And Arc Force

The arc and electromagnetic force were measured at different current levels. Table 4 lists the arc force measured and Table 5 the electromagnetic force. For all cases the forces were measured at 3 seconds after power-on and at torch-to-workpiece distance 4 mm. The reference measurement were made with argon flowing. The effect of the argon flow on the arc force measurement was eliminated by subtraction.

Figure 58 shows the relation between force and current squared. In Figure 58, "welding" indicates the force measured during arc welding and "reference" indicates the reference electromagnetic force measured. Solid lines shown in Figure 58 are least square fits of the experimental data. Linear relations appear, for both cases, between the measured force and the current squared. The standard deviation of the experimental data from the fit lines are 0.10 and 0.046 grams, respectively, which is small compared to the measured force.

The difference between these two lines in Figure 58 is the arc force which is shown in Figure 59. A linear relation between the arc plasma force and the welding current squared is consistent with theoretical prediction [37]. The proportionality factor between the arc plasma force and the
Fig. 58- Dependence of the electromagnetic force (reference measurement) and the arc force measured during welding versus current squared.
Fig. 59 - Dependence of arc force on welding current squared. Factor of proportionality equals 7.4x10^6, which is close to the value reported in [40].
Current squared is $7.4 \times 10^{-6}$ as expressed in Equation 20. In Figure 59, the experimental data has a standard deviation with respect to the fit line of about 0.04 gram which is small compared to the arc plasma force.

$$f_{\text{arc}} = C_f I^2 \quad (20)$$

where

- $f_{\text{arc}}$ is the arc plasma force, g.
- $I$ is the welding arc current, A.
- $C_f$ is the proportionality factor $= 7.4 \times 10^{-6}$ g/A$^2$.

The absolute value of the measured force depends on the experimental configuration but the arc force should be apparatus independent. To test that the procedure for arc force measurement is valid and independent of the experimental configuration, the welding arc plasma force was also measured at different locations on the test plate and at different distances between electrodes. A small difference of the arc force, about 6 to 13 percent of the arc force or less than 1 to 2 percent of the total force (measured during welding), was obtained which indicates validity of the arc force measurement.

Besides current measurements preliminary measurements of the effect of the arc gap on the arc force have also been made. The result is shown in Figure 60. In this experiment pool depression was not monitored. Generally, the arc force
Fig. 60- Relation between torch-to-workpiece distance and arc force.
is lower at a longer torch-to-workpiece distance as found in [39,41]. According to the conic arc model (Equation 5), a greater arc expansion, which usually exists at a longer arc length, should give a higher arc force, which is inconsistent with experiment. The effect of the type of shielding gas on the arc force as found in [26,41] cannot be predicted by Equation 5. The greater arc force at shorter arc length is probably because the arc plasma velocity is greater at a shorter distance from the electrode tip [26,38].

The relationship between arc force and arc length for a depressed pool is more complicated for a flat pool. The increase of arc length due to the increase of torch-to-workpiece distance is somewhat negated by decrease of the pool depression. In [26,38], no effect of pool depression on arc plasma velocity was reported. At this stage there is no theory which can predict the effect of the shape of the pool depression on the arc force. In addition, the electromagnetic force on the workpiece may depend on the shape of the arc, which varies with arc length. If this is so, the arc force was not quite properly calculated by simply subtracting the electromagnetic force.
Table 4: Force measured during welding at different current levels.

<table>
<thead>
<tr>
<th>Current</th>
<th>Exp. Force</th>
<th>No.</th>
<th>(g)</th>
<th>Current</th>
<th>Exp. Force</th>
<th>No.</th>
<th>(g)</th>
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<tbody>
<tr>
<td>100 A</td>
<td>f274</td>
<td>0.782</td>
<td></td>
<td>275 A</td>
<td>f252</td>
<td>5.98</td>
<td></td>
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<tr>
<td></td>
<td>f275</td>
<td>0.789</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>150 A</td>
<td>f276</td>
<td>1.748</td>
<td></td>
<td>300 A</td>
<td>f260</td>
<td>6.91</td>
<td></td>
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<tr>
<td></td>
<td>f277</td>
<td>1.889</td>
<td></td>
<td></td>
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<tr>
<td>175 A</td>
<td>f279</td>
<td>2.494</td>
<td></td>
<td>325 A</td>
<td>f248</td>
<td>8.362</td>
<td></td>
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<tr>
<td></td>
<td>f280</td>
<td>4.071</td>
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<td></td>
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<td></td>
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<tr>
<td>200 A</td>
<td>f265</td>
<td>3.31</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>225 A</td>
<td>f254</td>
<td>5.03</td>
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<tr>
<td></td>
<td>f263</td>
<td>4.98</td>
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Table 5: Measured electromagnetic force at different current levels.

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<tbody>
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<td>No.  (g)</td>
<td>No. (g)</td>
<td>No. (g)</td>
<td>No. (g)</td>
</tr>
<tr>
<td>200 A</td>
<td>f225 2.96</td>
<td>f223 6.257</td>
<td>f233 6.257</td>
<td></td>
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<tr>
<td></td>
<td>f226 2.996</td>
<td>f238 7.6</td>
<td>f239 7.569</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f227 2.948</td>
<td>f240 7.583</td>
<td>f239 7.569</td>
<td></td>
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<tr>
<td></td>
<td>f228 2.979</td>
<td>f241 5.409</td>
<td>f237 8.697</td>
<td></td>
</tr>
<tr>
<td>225 A</td>
<td>f244 3.633</td>
<td>f235 8.635</td>
<td>f236 8.704</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f245 3.604</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>250 A</td>
<td>f229 4.55</td>
<td></td>
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<tr>
<td></td>
<td>f230 4.533</td>
<td></td>
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<tr>
<td></td>
<td>f231 4.542</td>
<td></td>
<td></td>
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<tr>
<td>275 A</td>
<td>f241 5.409</td>
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<tr>
<td></td>
<td>f242 5.395</td>
<td></td>
<td></td>
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<td></td>
<td>f243 5.359</td>
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5.6 MEASUREMENT OF WELD POOL SURFACE TOPOLOGY

In this section, the work on weld pool surface depression measurement from radiographic images is described. The relations between material thickness, density, and radiographic image brightness levels were investigated. The weld pool surface depression was also related to the weld penetration obtained from weld cross sections made after welding.

5.6.1 Image Brightness-Material Thickness Relation

The relation between the radiographic image brightness level and the thickness of steel was found from radiographic images of steel step wedges. Figure 61 shows image brightness versus material thickness. Image brightness levels ranging from 255 (saturation level) to about 35 were obtained corresponding to steel thicknesses ranging from about 1.6 mm to 12.7 mm. Higher brightness levels were obtained for thinner materials because more penetrating radiation was received (positive image). Since the material thickness in the pool region should be less than the plate thickness, the radiographic parameters were adjusted to have greater contrast sensitivity for pool surface measurement. It can be seen in Figure 61 that the slope of the curve is
Fig. 61- Relation between radiographic image brightness level and material thickness for low carbon steel.
greater (higher contrast) for material thickness less than the plate thickness. The data presented in Figure 61 were taken at 150 KV tube voltage and 10 mA tube current.

The above radiographic measurement of the brightness-thickness relation was made at room temperature. During welding, because of the high temperature of the pool and the heat-affected zone, the material density changed and its effect on radiographic measurement has to be considered.

5.6.2 Computer Simulation of the Effect of Material Properties and Weld Pool Parameters on Radiographic Measurements

In this section, the effect of density change on radiographic measurement has been calculated by simulating radiographic attenuation in the weld. Figure 62 shows three regions: pool cavity (above the depressed pool surface), liquid layer, and solid base metal. The pool cavity has no radiographic attenuation. The other two regions are modelled by multilayered systems of discrete layers. Each layer has a different temperature and hence a different density. The effect of thermal expansion on radiographic measurement was also included. The overall radiographic attenuation was obtained by summing the attenuation of all the discrete layers.
Fig. 62- Weld pool geometry selected for computer simulation of the radiographic images.
In this work to express the temperature effect on image brightness level, a brightness ratio \( R \) and a correction factor \( k \) are introduced. The brightness ratio \( R \) relates the image brightness level with the temperature effect (\( B_1 \) in Equation 21) to the image brightness level without the temperature effect (\( B_2 \)). \( R \) is location dependent because of the cross-weld temperature distribution. Equation 22 shows the calculation of \( k \) which is the normalization of the brightness ratio of the pool region (\( R(y) \)) to the brightness ratio of the pool boundary (\( R(y_o) \)) where there is no pool depression (\( D(y) = D_o \)) and the pool surface temperature is near the melting point.

\[
R(y) = \frac{B_1(y)}{B_2(y)} \quad (21)
\]

\[
k(y) = \frac{R(y)}{R(y_o)} = \frac{\exp \left[ -\frac{\mu}{\rho_o} \left( \sum_{i=1}^{m} \rho_i(y) \Delta x_i(y) - \rho_o D(y) \right) \right]}{\exp \left[ -\frac{\mu}{\rho_o} \left( \sum_{i=1}^{n} \rho_i(y_o) \Delta x_i(y_o) - \rho_o D_o \right) \right]} \quad (22)
\]

where
- \( R \) is brightness ratio.
- \( k \) is correction factor.
- \( B_1 \) is brightness with the temperature effect.
- \( B_2 \) is brightness without the temperature effect.
- \( x \) is coordinate along the X-ray beam direction.
- \( \Delta x_i \) is thickness of discrete layer.
y is coordinate across weld.
\( D(y) \) is pool profile.
\( D_0 \) is plate thickness.
\( \mu \) is radiographic linear attenuation coefficient.
\( \rho_0 \) is material density at room temperature.
\( \rho_i \) is density of discrete layer.
i is index of discrete layer.
n is number of discrete layers in the pool.
m is number of discrete layers in the base metal.

The \( k \) value is certainly location dependent because of the cross-weld temperature distribution (hence density distribution) and pool depression. The effect of thermal expansion is also included in Equation 22 through the change of discrete layer thickness, \( \Delta x_i \). When the temperature is constant the brightness ratio \( R \) and correction factor \( k \) equal one everywhere.

Pool surface temperature is assumed to be maximum at the pool center and to decrease exponentially to the pool boundary and heat-affected zone (the region below the liquid metal whose temperature is below the melting point of steel, about 1532 degrees C). A peak pool surface temperature of 2300 degrees C. was assumed at the pool center which is about the same value used in [64] and slightly higher than the value assumed in [24]. Plate thickness 10 mm and maximum
pool depression 2 mm at pool center are assumed. In the calculation experimental data on temperature-density [33] and temperature-thermal expansion [36] relations were used. Radiographic attenuation coefficient 1.25 1/cm was assumed. From these values the effect of temperature on radiographic measurement was calculated using Equation 22.

Figure 63 shows the correction factor. Correction factor values ranging from 0.97 at the pool center to 1 at the pool boundary are obtained. The correction factor is minimum at the pool center because the temperature is highest and the liquid layer is thickest. The maximum difference of the correction (at pool center) is about 3 % which is in the range of the noise level of the radiographic images. Thus, because of the small difference of k values, the effect of temperature on radiographic measurement is practically negligible.

5.6.3 Experimental Determination of Weld Pool surface Topology and Pool Depression

Based on the experimentally obtained image brightness-thickness relation (Figure 61), weld pool surface topology was determined from radiographic images. Linear interpolation of material thickness between data points in Figure 61 was used. An example of pool depression measured
Fig. 63- Brightness correction factor due to temperature related density change obtained from computer simulation. The maximum correction difference (at pool center) is about 3% which is in the range of the noise level of the radiographic images.
from radiographs for low carbon steel is shown in Figure 64 together with the weld penetration measured metallographically from the weld cross-section. The liquid metal layer in the pool is contained between these two lines. For this particular case with a welding current 344 A and welding time 4 seconds, the thickness of this liquid layer was found to be less than 1 mm. The contrast sensitivity of the radiographic system was measured to be about 2 %. Hence, the accuracy of the radiographic thickness measurement is about 0.2 mm based on 2 % contrast sensitivity for a 9.5 mm thick steel plate.

In addition to the accuracy of measurement, the minimum detectable pool depression is also determined by making smaller weld pool depressions at lower currents. Figure 65 gives an example of the threshold of detection of pool depression. In Figure 65, the images were taken from 0 to about three seconds of welding time (from left to right) and image brightness has been expanded to increase the image contrast. Figure 65 (A) shows radiographic images of the weld pool made at 225 A where a small depressed pool surface can be seen as a small white circle in front of the electrode. Figure 65 (B) shows radiographic images of the weld pool made at 200 A where no pool depression can be detected and the weld penetration was found (by cutting the sample after welding) to be about 1.5 mm. In addition, the
Fig. 64—Experimental cross-sectional profiles of the weld pool on low carbon steel. Pool surface profile measured by radiography. Weld penetration measured by weld cross-sectioning after solidification. Welding current was 344 A, welding time 4 seconds, and torch-to-workpiece distance 4 mm.
Fig. 65- Radiographic images of the low carbon steel weld pool: (A) made at 225 A where a small depressed pool surface can be seen as a small white circle in front of the electrode. (B) made at 200 A where no pool depression was found.
heat-affected zone, which is at a relatively higher temperature than the base metal, could not be differentiated from the base metal (Figure 48). This verifies the previous simulation result that the effect of material density change on radiographic measurement is negligible.

In order to further verify that the reconstruction procedure for pool depression is valid, the volumes of the pool depression (empty space) and the hump area (liquid metal) around the pool were calculated separately to examine liquid mass conservation of the pool. The pool volume was calculated by discretizing the rings as shown in Figure 66. Each ring has a constant (unit) width ($\Delta x = \text{pixel size}$) but is different in height and diameter. The volume of each ring can be calculated from the cross-sectional profile of the pool depression; axial symmetry was assumed. In Figure 66, $V_B$ is the inner ring at the pool center and $V_A$ is a ring at the pool hump region.

Figure 67 shows the pool volume distribution. In Figure 67, the volume distribution of pool rings is plotted versus cross-weld location. The volume was obtained by summation of the ring volumes in the depressed and hump regions. For the particular case shown in Figure 67, the volume of the pool cavity region (32 mm$^3$) was found to be roughly the same as the volume of the pool hump region (31.5 mm$^3$). The small difference, less than 2%, indicates that the pool mass is
Fig. 66- Schematic of weld pool surface profile and pool section ring for liquid metal volume conservation measurement.
Fig. 67- Experimentally measured elemental volume distribution of pool cavity and pool hump.
conserved.

In summary, we have demonstrated that with the technique developed the weld pool surface topology can be quantitatively measured during welding. The determination of the liquid layer thickness between the arc plasma-liquid interface and the liquid-solid interface is also important. We have used this method for study of the effect of pool shape on weld formation, the results of which will be discussed in the following chapter.

5.7 SUMMARY

In this work a new technique for simultaneous measurement of weld pool depression by radiography and arc force by a balanced force measuring device has been developed and evaluated. A floating electrical contact between the part and ground has been used to improve force measurement. The accuracy and the zeroing error of the force measuring device were determined to be within 0.05 gram. A linear relation between arc force and current squared was found, which is consistent with theoretical prediction.

The precision of pool depression measurements is about 0.2 mm. The effect of temperature related material density change on radiographic measurement was found to be negligible by computer simulation of the radiographic
images. Pool surface geometry including humping on the pool periphery has been reconstructed. The volumes of the pool depression (empty space) and the hump area of the liquid metal around the pool were calculated separately and conservation of pool mass was verified. The thickness of the liquid layer between the arc plasma-liquid interface and the liquid-solid interface was determined by comparison of the pool depression with the weld penetration.
6.1 INTRODUCTION

This chapter describes a study of the arc plasma-weld pool interaction focusing on the relations between welding parameters, arc force, pool depression, surface tension and gravitational pressure, weld penetration, and pool stability. A technique used here for real-time simultaneous measurements of the weld pool surface geometry and the arc force was described in the previous chapter.

The interaction between the welding arc and the molten pool is the heart of arc welding. It determines the pool behavior and the weld penetration. The arc-pool interaction is even more important when high welding current is used for high productivity. In this case the molten pool surface becomes depressed and its shape significantly affects the welding process. The phenomenon of pool depression is related to pool stability, weld formation, and formation of
weld discontinuities, so study of the arc-pool depression is fundamental for arc welding. The diversity of the welding parameters, the complexity of their relationships, and the hazards of the welding environment create difficulties in such a study.

The surface tension pressure is one of the most important forces opposing the arc force and it also affects the pool formation. Surface tension driven pool motion which affects weld penetration was found by Oreper et al. and Choo et. al [21,24]. A self-suspension full penetration pool, with a flat pool surface and no arc force considered, has been studied by Matsunawa and Ohji [35] to determine the allowable pool size. Lin and Eagar and Lancaster [26,53] by assuming a hemispheric pool depression (constant surface curvatures), estimated the pool surface tension force. Most quantitative experimental studies of the welding process have been restricted to a water-cooled copper anode or a flat pool surface, while in reality the pool surface is clearly depressed at high currents. Theoretical studies have demonstrated the importance and complexity of the effects of pool surface depression on the arc plasma-pool interaction and on weld penetration [24,26,42,53,77]. It is known from the previous chapter that a typical pool depression has a more complicated shape than a hemispheric shape. In addition, it is known that there exists a hump area at pool
boundary which also has some effect on calculation of the reconstructed force.

The objective of this chapter is to study the arc force and weld pool depression, penetration, and stability by real-time radiography combined with a balanced force measurement device. First the technique and experimental methodology will be briefly discussed and then the relationship between the welding current, the arc force, and the pool depression will be established. Calculations of the surface tension and gravitational pressures were done based on the depression of the pool surface and the surface tension. Relationships between the pool depression and the weld penetration will be studied. Preliminary results on stability of the depressed pool and real-time observations of pore formation in the welding pool will also be given. The results may help to formulate boundary conditions for computer modelling of the arc plasma jet-liquid metal interface. This work can also lay the foundation for development of new algorithms for welding penetration control and in-process weld quality control, which will be described in the next chapter.
6.2 EXPERIMENTAL INVESTIGATION OF ARC-POOL INTERACTION

To investigate the arc-pool interaction the pool depression and the arc force were simultaneously measured at different current levels. One frame from a sequence of positive radiographic images of the molten pool taken during stationary GTA welding on low carbon steel is shown as a typical example in Figure 48. The circular white area in front of the tungsten electrode is a depressed welding pool. The dark circle surrounding the white area corresponds to a humped region on the periphery of the pool. A quantitative technique to reconstruct the pool depression profile from the radiographic images has been developed and is explained in the previous chapter.

6.2.1 Arc Force-Current Relation

The results of the arc force measurement (solid triangle) versus current squared were summarized in Figure 68. The data from Burleigh and Eagar [40] (solid square) are also shown for comparison. A linear relation between the arc force and the current squared was found as shown in Figure 68. This is consistent with theory [37]. A slight difference in the measured arc force was found between the present work and Burleigh and Eagar [40]. In the present work the arc
Fig. 68—Relation between welding arc force (solid triangle) and current squared for low carbon steel. Solid line is the least square fit of experimental data. The data from Burleigh and Eagar [40] (solid square) are also shown for comparison.
force, which reaches steady values within about 1.5 seconds, was measured at 3 seconds after power-on and at torch-to-workpiece distance 4 mm. The effect of the argon flow on the arc force measurement was small, less than 0.05 gram, and eliminated by subtraction. The proportionality factor between the arc plasma force and the current squared found in this work is $7.4 \times 10^{-6}$ as expressed in Equation 20.

Arc pressure, which is the electromagnetic (Lorentz) force exerted on the welding pool, is due to the flow of electric current provided by the welding power supply and the self-generated magnetic field around the welding arc. This electromagnetic force induces an arc plasma jet which impinges on the welding pool and is possibly strong enough at high welding current to produce a depressed pool surface.

Based on the magnetohydrodynamic theory of an ideal conducting liquid with a homogeneous current distribution across the cross section of the arc, a simple approximate relation between arc force and current was formulated [76]. The theoretical proportional factor $(\mu_0/8\pi)$ is about three times lower than the proportional factor obtained from the direct arc force measurement. The major weakness of this model is the lack of dependence of the arc force on the shape of the arc.

A welding arc was modelled as a cone by Converti [37] which is closer to the real arc shape than the above
cylindrical arc shape. The conic shape is caused by the constriction of the current at the cathode which is related to the welding current. To some extent, arc expansion may be related to the welding current, and therefore to the arc force. The relation between arc force, current, and arc expansion \( \frac{R_2}{R_1} \) is expressed in Equation 5 [37]. For constant arc expansion, the arc force is linearly proportional to the current squared.

Lack of consideration of the effect of the pool depression shape on the current density distribution [24], and therefore on the arc force, is the principal disadvantage of the conical arc modelling. The arc force also depends on the arc length as was previously shown and on the electrode tip angle, the type of shielding gas, and the base metal [26,41], none of which enter Equation 5.

From the data shown in Figure 68, \( \frac{R_2}{R_1} \) is about 3 for the present work which is close to the value \( \frac{R_2}{R_1} = 4 \) for Burleigh and Eagar [40]. For \( \frac{R_2}{R_1} = 3 \) to 4 and electrode diameter 3.175 mm (the maximum possible value of \( R_1 \)), the maximum arc radius \( R_2 \) at the base metal is less than about 12 mm. For this particular case with argon shielding and 4 mm torch-to-workpiece distance, this value is slightly less than the maximum weld pool width and greater than the pool depression width measured in the present work (results will be presented below) which is reasonable.
6.2.2 Pool Depression-Current Relation

Typical pool depression shapes measured at different current levels by real-time radiography are shown in Figure 69. It can be seen in Figure 69 (A) that pool depression at 225 A is small (shallow and narrow). As the current increases, the pool depression increases, partly due to the stronger arc force, as can be seen in Figure 69 (B) through (F) for current from 250 A to 350 A. Data shows that the pool depression depth increases faster than the width.

The results of pool depression measurements at different current levels are summarized in Figure 70. A clear linear dependence of pool depression on current squared was found in the range from 200 A to 350 A. It can be seen in Figure 70 that the pool surface begins to be depressed at currents about 200 A. Since the arc force was found in [26,41] to depend on the electrode tip angle, arc length, type of shielding gas and surface tension, this current level is expected to depend on the actual experimental conditions. From experimental data for depths of pool depression we have the following empirical equation, 23:

\[ D_{\text{pool}} = -p + qI^2; \text{ for } 200A < I < 350A \ (23) \]

where

\[ D_{\text{pool}} \] is the depth of pool depression, mm.
Fig. 69—Typical shapes of pool depression measured on low carbon steel at different current levels by real-time radiography, 3 second welding time.
Fig. 70- Pool depression on low carbon steel versus current squared. A linear dependence of pool depression on current squared is found. The pool surface begins to be depressed at currents about 200 A. The depression width increases relatively rapidly at low current and saturates at high current.
p is a constant = 1.675 mm.
q is the proportionality factor = 4.124 \times 10^5 \text{ mm}/A^2.

Also shown in Figure 70 is the width of pool depression versus current squared. The depression width increases relatively rapidly at low current and saturates at high current. Based on the information shown in Figures 69 and 70, I suggest that the arc plasma jet is not only stronger at higher current but is also more concentrated. In a study of a welding arc on a water-cooled copper anode [26], an arc plasma distribution which depended on the type of shielding gas and the electrode tip angle was also found.

The amount of liquid metal being pushed aside by pool cavity formation has been roughly estimated by modelling the cavity as a cone with the same depth and width as the actual pool depression. The results are shown in Figure 71. In the previous chapter, the volumes of the pool cavity (empty space) and the hump area (liquid metal) around the pool were precisely calculated and found to be equal to the volume of the pool hump region. The volume of the depressed cavity is about the same as that estimated from the volume of the cone. For example at 350 A, shown in the figure as a solid triangle, 31 \text{ mm}^3 was calculated from pool depression which is close to the volume estimated from the cone (27 \text{ mm}^3).
Fig. 71- The amount of liquid metal being pushed aside by arc plasma to form pool cavity versus current squared. The solid triangle was calculated from pool depression which is close to the volume estimated from the cone.
6.2.3 Arc Force-Pool Depression Relation

There are several pool depression formation mechanisms. The arc force is one of the principle ones. Since, in the studies above, both arc force and pool depression were found to be proportional to the current squared, a linear relation between arc force and pool depression is expected. Figure 72 shows the linear dependence of pool depression on arc force in the current range from 200 A to 350 A. The linear relation is expressed in Equation 24. Figure 72 also shows that the pool surface begins to be depressed at an initial arc force of about 0.35 gram. The initial arc force, as well as the values 'C₁' and 'C₃' in Equation 24, depends on the material surface tension and density. A linear arc pressure-pool depression relation was also found for the partially penetrated weld pool in a computer simulation [42]. In [42], arc pressure was considered to be the major cause of pool depression.

\[ D_{pool} = -C_s + C_d f_{arc} ; \text{ for } 200A < I < 350A \] (24)

where

- \(D_{pool}\) is the maximum depth of pool depression, mm.
- \(C_s\) is constant for a given material, here = 1.831 mm.
- \(C_d\) is the proportionality factor = 5.533 mm/g-f.
Fig. 72 - Linear relation between pool depression and arc force. The pool surface begins to be depressed at an initial arc force of about 0.35 gram. A linear arc pressure-pool depression relation was also found in [42]. It is known that pool depression formation also depends on other factors. Refer to the text about details of pool depression mechanisms.
In order to interpret the initialization and growth of pool depression, the formation of pool depression at different current levels is illustrated in Figure 73. In Figure 73 (A), a slightly convex pool surface can be seen. This occurs because the liquid metal has greater volume in the liquid than in the solid phase. To produce a pool depression on a surface, a finite arc force is required. A pool surface with a small depression can be seen in Figure 73 (B). In the previous chapter, the threshold current for pool depression was found to be about 200 A for steel, which corresponds to an arc force about 0.35 gram as shown in Figure 72. As current increases further, the depressed pool surface becomes deeper (Figure 73 (C)) partly because of a higher arc force. Since the arc force and its distribution depend on electrode tip angle, arc length, and type of shielding gas, the threshold arc current for pool depression varies for different welding conditions and materials.

The above discussion is mainly based on the assumption that the arc force is the dominant factor in pool depression. However, it is known that pool depression formation also depends on other factors. In the present work, a slight depression of the liquid gallium pool (non-arc) was observed around the electrode at currents above 300 A. This indicates the effect of the electromagnetic force on pool depression. Such an effect was found to be small since
Fig. 73- Schematic of initialization and growth of pool depression at different current levels. (A) A slightly convex pool surface can be seen. This occurs because the liquid metal has greater volume in the liquid than in the solid phase. (B) To produce a pool depression on a surface, a finite arc force is required. The threshold for pool depression was found to be at a current of about 200 to 225 A on steel. (C) The depressed pool surface becomes deeper as current increases further.
this force acts on a wider area than the arc force does. In addition, liquid gallium has a surface tension about 40% of the surface tension of liquid iron at their respective melting temperatures [26,75]. Therefore, a gallium pool is more easily depressed than a steel pool. Pool convection was also found to contribute to the pool depression [53,77]. A comparison of arc and non-arc forces will be presented below.
6.3 RECONSTRUCTION OF SURFACE TENSION FORCE FROM POOL DEPRESSION

The surface tension pressure is one of the most important forces opposing the arc force and it also affects the pool formation. Comparing the reconstructed surface tension force with the directly measured arc force is important in a study of the mechanisms of pool depression formation.

In most previous work on the surface tension force \[26,53\], the pool depression was assumed to have a hemispherical shape. From this assumption the surface tension force was calculated. Certainly a hemisphere which has constant surface curvatures oversimplifies the actual pool depression.

A typical pool depression has a more complicated shape (Figure 64) and the hump area must also be included in the calculation of the surface tension force. In this section the surface tension pressure distribution was calculated based on the experimentally obtained pool topography and the surface tension. The gravitational pressure distribution was also determined. The surface tension (a material property), surface tension pressure, and surface tension force are explained in the following section.
6.3.1 Mechanisms of Surface Tension

Within the body of a liquid, the net force on any given molecule is relatively small; it is surrounded by a group of other molecules which exert forces in all directions so that there is little or no resultant. When a surface is formed, the molecules in the surface layer have a entirely different environment on one side. The interfacial region is characterized \cite{78,88,89} by the thin layer of a few molecules thickness which separates two bulk regions, within which the physical properties differ from those in either of the bulk regions. Free surface energy arises from the strong inward attraction exerted on surface molecules by the underlying molecules, perpendicular to the surface, which tends to minimize the surface area. That extra energy at the interface is called the surface free energy $F^E$ as defined in Equation 25.

$$F^E = F - (F_1 + F_2) \quad (25)$$

where

$F^E$ is the surface free energy.

$F$ is the total free energy of two phase system including interface.

$F_1$, $F_2$ is the free energy of each bulk phase.
In case of the one-component systems, the surface free energy $F^S$ is a thermodynamic potential for which temperature $T$ and surface area $\Sigma$ are the independent variables. Therefore, the following notation is used.

\[ dF^S = (\frac{\partial F^S}{\partial T})_\Sigma dT + (\frac{\partial F^S}{\partial \Sigma})_T d\Sigma \]

\[ = -S^S dT + \gamma d\Sigma \quad (26) \]

where

$T$ is temperature.

$\Sigma$ is surface area.

$S^S$ is the surface entropy.

Compared to the bulk liquid, the surface region has an extra degree randomness since a molecule may occupy a position either in the immediately subjacent bulk phase or at the surface. This increases the entropy and this is the entropy change associated with surface formation. The quantity $\gamma$ is the free energy per unit area of the surface at constant temperature, or the work which must be done to increase the area of the surface by one unit. Since the free surface energy tends to a minimum, the surface will always tend to contract spontaneously and work must be done to extend the surface, for example by the arc force. This tendency is shown in the spherical form of small drops of liquid as they tend to become less extended and the pool surface depression as it tends to become flat.
\[ \gamma = \left( \frac{\partial F^E}{\partial N} \right)_T \] (27)

where

\( \gamma \) is the surface free energy per unit area at constant temperature, usually called interfacial tension or surface tension, J/m\(^2\) or N/m.

It is obvious that the work of reversible isothermal expansion of the surface, \( dW \), is equal to the decrease in free energy, i.e.,

\[ dW = -\gamma d\Sigma \] (28)

where

\( dW \) is the work of reversible isothermal expansion of the surface \( d\Sigma \).

and hence the quantity \( \gamma \) is usually called interfacial tension or surface tension and has the unit of J/m\(^2\) or N/m. The surface free energy in a one-component system is fully determined by two parameters, for example by the temperature \( T \) and surface area \( \Sigma \). The surface tension \( \gamma \), therefore, is a function of temperature. The surface tension was also found to depend on the type and contents of the surface active elements by Keene et al. [34].
6.3.2 Pressure Differences across a Curved Liquid Surface
(Surface Tension Pressure)

The curvature of a curve at a point is the limit of the ratio of the angle between a tangent vector at this point and a tangent vector at a neighboring point on the curve to the arc connecting these two points as the neighboring point approaches the point along the curve [81,82]. The curvature at a point may vary at different normal sections at the point. The maximum and minimum curvatures at a point are called "principal curvatures".

When a liquid surface is curved as shown in Figure 74, the pressure ($P_1$) is greater on the concave side than the pressure ($P_2$) on the convex. The difference ($P_1 - P_2$ called surface tension pressure) depends on the surface tension and on the principal curvatures [78]. When the curved surface moves towards the convex side, work, which is supplied by the pressure difference moving the surface, has to be done to increase the area. The increase of surface area is related to the principal curvatures [78]. To maintain minimum surface energy, a liquid surface has to have minimum area.

The area of the element of surface after the displacement is
Fig. 74- Surface area increase caused by pressure difference across a curved liquid surface [78].
\[ (AB + \frac{AB}{R_1} \delta n)(BC + \frac{BC}{R_2} \delta n) \] (29)

or, neglecting the second-order quantities,

\[ ABCD (1 + \frac{\delta n}{R_1} + \frac{\delta n}{R_2}) \] (30)

The work done against the free energy of surface tension \( \gamma(T) \) of the surface is therefore

\[ \gamma(T) ABCD \delta n \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \] (31)

The work done by this pressure difference \((P_1 - P_2)\) is

\[ (P_1 - P_2) \delta n ABCD \] (32)

If no work is done by any other forces, hence these quantities are equal and

\[ P_s(x, y, T) = P_1 - P_2 = \gamma(T) (\kappa_1(x, y) + \kappa_2(x, y)) \] (33)

where

- \( x \) and \( y \) are the coordinates with \( x \) in the cross-weld direction and \( y \) in the along-weld direction.
- \( \kappa_1 = 1/R_1 \) and \( \kappa_2 = 1/R_2 \) are the principal curvatures of the surface.
- \( \gamma \) is the surface tension.
- \( T \) is the temperature.
- \( P_s \) is the surface tension pressure, with direction perpendicular to the surface.
In this work, for a point on a two-dimensional pool surface as shown in Figure 75 (A), the surface tension pressure, \( P_s(x,y,T) \), was calculated from the two principal curvatures, \( \kappa_1(x,y) \) and \( \kappa_2(x,y) \), and the surface tension, \( \gamma(T) \), as expressed in Equation 33. The principal curvatures were calculated from information on the pool surface shape. The surface tension was found to depend on the material components and the temperature by Keene et al. [34]. The surface tension measured during welding was found to be similar to the surface tension measured not during arc welding by Wen and Lundin [86].

In Figure 75 (B) \( d\Sigma \) is a small area with pressure \( P_1 \) on one side of the pool surface acting on point 'A' and pressure \( P_2 \) on the other side. The reconstructed force 'F' (the surface tension and gravitational forces) was calculated by integrating the surface tension \( (P_s) \) and gravitational pressures \( (\rho \, g \, z) \) around the area \( (\Sigma) \) of pool as given by Equation 34.

\[
F = \int_\Sigma [\gamma(T) (\kappa_1(x,y) + \kappa_2(x,y)) \cos \theta + \rho \, g \, z] \, d\Sigma \tag{34}
\]

where

- \( F \) is the reconstructed force.
- \( \Sigma \) is the surface area.
- \( \rho \) is material density.
- \( g \) is the acceleration of gravity.
Fig. 75- Surface tension. (A) Relation between surface tension and pressure differences across a depressed pool surface. (B) Pressure balance on a small surface area $d\Sigma$. 
\( \theta \) is the angle between surface normal (n) and the vertical (z) axis.

6.3.3 Two-Dimensional Quadratic Least-Square Approximation of Pool Depression and Surface Curvatures

A typical pool depression profile is shown in Figure 64. In this section, the two-dimensional surface geometry, the height \( z = f(x,y) \), was approximated locally by a quadratic function, \( f_a(x,y) \) as expressed in Equation 35, using the least-squares method. The method of reconstructing the shape of the pool depression from radiographic images was described in the previous chapter.

\[
f(x,y) = f_a(x,y) = C_{00} + C_{10}x + C_{01}y + C_{11}xy + C_{20}x^2 + C_{02}y^2 \quad (35)
\]

where

- \( f(x,y) \) is the surface geometry.
- \( f_a(x,y) \) is the approximated quadratic function of \( f(x,y) \).
- \( C_{00}, C_{10}, \ldots, C_{02} \) are the coefficients of \( f_a(x,y) \).

For a quadratic function, the principal surface curvatures are determined by the eigenvalues of the matrix of coefficients of the second order terms [82]. The curvatures are independent of the orientation of the surface. In this work at a point on the pool surface, the
principal curvatures were determined by the elements of the matrix C in Equation 36. The two eigenvalues of this matrix are the two principal curvatures of the surface, $\kappa_{1,2}$ as expressed in Equation 37. The surface orientations, which were also needed in the integration of surface tension and gravitational pressures to obtain the reconstructed force, are determined by the linear terms.

$$
(C) = \begin{pmatrix}
  C_{20} & \frac{1}{2} C_{11} \\
  \frac{1}{2} C_{11} & C_{02}
\end{pmatrix} \quad (36)
$$

$$
\kappa_{1,2} = \frac{C_{20}+C_{02}}{2} \pm \frac{1}{2} \sqrt{(C_{20}-C_{02})^2 + C_{11}^2} \quad (37)
$$

In order to obtain the six coefficients, the above quadratic function, $f_\alpha$, was found by using six linearly independent orthonormal unit vectors (the orthonormal bases), $u_m$ in Equation 38. Six linearly independent unit vectors are needed because the six unknown coefficients of $f_\alpha(x,y)$ need to be found and it is simpler using orthonormal bases than non-orthonormal bases. Then the coefficients of $f_\alpha(x,y)$ can be calculated from the $e_m$ which are given by the inner product of $f(x,y)$ and $u_m$ as shown in Equation 39.
\[ f_a(x,y) = \sum_{m=1}^{6} e_m u_m \] (38)

\[ e_m = \langle f, u_m \rangle \] (39)

where

\( u_m \) is the six-dimensional orthonormal unit vector.

\( f(x,y) \) is the surface geometry.

Finding the orthonormal basis functions is critical to the least-squares fit for pool depression. The orthonormal basis is obtained by the Gram-Schmidt orthogonalization process [83,84]. Equation 40 expresses six orthogonal basis functions and \( c \) is a constant needed for orthogonalization. This system is orthogonal only on a square region centered at the origin. For the discrete case, the orthonormality was numerically verified by computer and the constant \( c \) is given by Equation 41 with \( n_1 = n_2 \). The denominator in Equation 41 is used for normalization. The unit vectors \( u_m \) are given in Equation 42. By inserting \( u_m \) and \( e_m \) into Equation 35, the coefficients of \( f_a(x,y) \) were obtained as expressed in Equation 43.
\[ w_1 = 1; \quad w_2 = x^2 - y^2; \quad w_3 = xy; \]
\[ w_4 = x^2 + y^2 - c; \quad w_5 = x; \quad w_6 = y; \quad (40) \]

\[ c = \sum_{i=-n_i}^{n_i} \sum_{j=-n_j}^{n_j} (i^2 + j^2) \]
\[ \frac{(2n_i+1)(2n_j+1)}{2} \quad (41) \]

\[ u_m = \frac{w_m}{k_m}, \quad m = 1, 2, \ldots , 6 \quad (42) \]

\[ f_a(x, y) = \left( \frac{e_1}{k_1} + c \frac{e_4}{k_4} \right) + \frac{e_5}{k_5} x + \frac{e_6}{k_6} y + \frac{e_3}{k_3} xy + \]
\[ \left( \frac{e_2}{k_2} + \frac{e_8}{k_8} \right) x^2 + \left( \frac{-e_2}{k_2} + \frac{e_1}{k_1} \right) y^2 \quad (43) \]

where

\[ w_1, w_2, \ldots , w_6 \] are the orthonormal basis.

\[ k_m = \| w_m \| \] is the norm of \( w_m \).

\( n_i \) and \( n_j \) are the window sizes along the x and y directions, \( n_i = n_j \).

The coefficients of \( f_a(x, y) \) were numerically calculated for a point on pool surface, yielding the two principal curvatures at this point (Equation 37). By repeatedly doing this, distribution of pool surface curvatures was obtained, thus distribution of the surface tension pressure was calculated (\( P_s(x, y, T) \) in Equation 33). In the calculation, the optimal window size of the image was chosen to have the minimum normalized squared error, as defined by Equation 44.
To calculate the reconstructed force the surface tension and gravitational pressures were integrated over the whole pool surface (Equation 34). The surface direction given in Equation 45 was used to calculate the vertical (to the workpiece) component of the surface tension force. The gravitational pressure, $P_g$, can be calculated from the depth of the pool depression $f_a(x,y)$, given by Equation 46.

Because of the high surface tension of liquid metal pool, the gravitational pressure, $P_g$, is usually smaller than the surface tension pressure, $P_s$.

\[
\cos(\theta) = \frac{1}{\sqrt{(C_{10}^2 + C_{01}^2 + 1)}} \quad (45)
\]

where

$\theta$ is the angle between surface normal and the vertical (z) axis.

\[
P_g(x) = \rho g f_a(x,y) \quad (46)
\]

where

$P_g$ is the gravitational pressure.

$\rho$ is the density.

$g$ is the acceleration of gravity.
6.3.4 Effects of Surface Temperature Distribution on Surface Tension

Information on the dependence of surface tension on temperature and surface active elements is as important as knowledge of pool geometry. The arc current density distribution, which is affected by the shape of the pool depression, is one of the most important factors in the determination of pool surface temperature.

Figure 2 shows a flat pool with a Gaussian current density distribution from a 200 amp arc [24,25]. In the present study, it is known that the pool surface is flat at 200 A since the current is below the threshold for pool depression (Figure 70). The distribution becomes bimodal because of the depressed pool surface at higher current. Figure 76 shows a depressed pool with a bimodal current density distribution from a 300 amp arc. The data in Figure 76 were obtained from welding arc simulation [24] where pool depression was used as an input. Apparently the arc current density distribution is affected by the shape of the depressed pool surface (compared to Figure 2). For a bimodal distribution (Figure 76), the maximum current density at 300 A was found at the pool hump (also the hottest region) and was lower at both the pool center and the boundary (the cooler region). The maximum current density of a 300 A arc
Fig. 76- Bimodal current density distribution at 300 A [24].
is even smaller than the maximum current density of a 200 A arc (at the pool center in Figure 2). Partly because of the lower current density in the pool center, the pool center is expected to be relatively cooler than the pool hump.

Surface temperature was assumed to have a distribution similar to the current density. Both Gaussian and bimodal distributions were tested. At the maximum current density, 5.5 A/mm² in Figure 2, maximum surface temperature 2500 deg. C was assumed. The melting point temperature was assumed at the pool boundary for the Gaussian distribution (Figure 2) and at the pool center and boundary for the bimodal distribution (Figure 76) with current density about 0.04 A/mm². The surface temperature across the pool was assumed to vary linearly with current density. Uniformly distributed surface tension was also tested.
6.3.5 Results and Discussion

In this study of a stationary GTA welding pool, the principal surface curvatures $\kappa_{1,2}$, were calculated from the pool profiles. Figure 77 illustrates the windowing of radiographic image for two-dimensional approximation of pool depression and surface curvatures. A depressed pool has a typical shape which consists of two regions: a concave pool cavity and a convex pool hump. At point 'P' on pool surface using the method described above, the approximate pool height $z=f$, and the principal surface curvatures $\kappa_1$ and $\kappa_2$ were calculated at this point, based on the neighboring surface shape (window ABCD). By repeatedly doing this across the pool center (along the line 'L'), distribution of the approximated pool height and the principal surface curvatures were calculated. An $11 \times 11$ pixel window ($2.4 \times 2.7$ mm) was used. The window size was selected to minimize the normalized squared error (Equation 44).

Figure 78 (A) shows the result of reconstructed pool surface for the case of 350 A and distribution of $\kappa_1$ and $\kappa_2$ (taking concave shape to be positively curved) with three distinct regions. The first principal curvature $\kappa_1$ is found to be positive and the second curvature $\kappa_2$ is positive only at pool center. In region I which is at the center of pool cavity, $\kappa_1 + \kappa_2$ is positive (indicates a concave pool shape)
Fig. 77- Schematic of approximation of pool depression and surface curvatures.
Fig. 78- Calculated principal surface curvatures $k_1$ and $k_2$. (A) Two-dimensional quadratic least-squared fit (solid line) of experimentally obtained (solid dots) pool depression profile on low carbon steel. Welding current was 350 A and torch-to-workpiece distance 4 mm. (B) Pool depression and the sum of principal curvatures.
as shown in Figure 78 (B). The maximum $\kappa_1 + \kappa_2$ is found at pool center, about 0.57 mm. In region II which is at about the boundary of pool cavity, the $\kappa_1 + \kappa_2$ varies from positive (concave shape) to negative (convex shape) as approaching the boundary of pool cavity. In region III which is at the pool hump, the $\kappa_1 + \kappa_2$ is negative (still convex shape) and increasing, eventually zero (becomes flat).

The curve of curvatures is about symmetrical except at point 'A' in Figure 78 (A) which is caused by the corresponding small change of pool depression. The symmetry of pool depression was also verified by examining the corresponding profiles at each side of the pool.

As discussed above the pressure difference is related to the sum of the principal curvatures. In Figure 78 (B) a positive $\kappa_1 + \kappa_2$, which indicates a high pressure on the concave side due to arc force, can be seen in the pool center due to its concave shape. At the pool hump, the pool shape is convex and negative curvatures occur. This is possibly caused by the liquid flow which is pushed aside by the arc plasma. Near the pool boundary the pool surface is flat and curvatures were found to be zero. Certainly the pool curvatures are not constant and more complicated than a hemisphere shape assumed in [26,53].

From the surface shape, surface tension and density, distributions of surface tension pressure and gravitational
pressure were obtained as shown in Figure 79. The surface tension pressure has a greater amplitude (several times greater) than the gravitational pressure. Thus the surface tension force is proved to dominate the gravitational force. Note that in the pool hump region (regions A and C), both surface tension and gravitational pressures are negative. This means both pressures tend to minimize the pool hump region.

The maximum pressure, 1176 N/m² with 937 N/m² and 239 N/m² from surface tension and gravitational pressure respectively, obtained in this study at 350 A, is about twice lower than the arc plasma pressure obtained in [26], i.e. 1800 N/m² at 300 A and 2700 N/m² at 400 A. This is partly because the velocity of arc plasma jet decreases at a longer distance. For the current study, the distance includes the torch-to-workpiece distance (4 mm) and the depth of pool depression (about 3 mm). In [26], measurement was done on water-cooled copper anode and no pool depression was involved in the measurement of arc plasma pressure.

Arc plasma pressure calculated based on the kinetic energy of arc plasma jet was also found in [26]. For example arc plasma velocity 200 m/s measured at 300 A gives arc plasma pressure about 2000 N/m². Due to the same token that no pool depression was involved in the measurement of arc plasma velocity, the calculated arc plasma pressure was
Fig. 79- Calculated distributions of surface tension and gravitational pressures.
found higher than the present study.

The surface tension and gravitational forces were calculated by integrating the surface tension and gravitational pressures across the pool center on a pixel wide stripe (Figure 77). The total reconstructed force was approximated by integrating the surface tension and gravitational forces over a half circle. First uniformly distributed surface tension was used in calculation. The results are shown in Figure 80. The reconstructed sum of surface tension and gravitational forces was found to be about 2.1 to 2.4 grams depending on the surface tension. Also shown in Figure 80 is the arc force measured at the same current (350 A), 0.9 gram. The difference between the reconstructed force and the arc force is the non-arc force. For a bimodal surface tension distribution a similar reconstructed force, about 2.2 grams, was also found. In Figure 80 the increase of force as surface tension increases is because a positive surface tension-temperature coefficient was assumed in calculation due to the high sulfur content of steel [34].

A reconstructed force greater than the arc force was also obtained by Lin and Eagar [53] by assuming a hemispherical pool surface (constant surface curvature) and constant surface tension. In a study of pool convection [18] the pool vortex was found to be the major contribution to
Fig. 80- Comparison between reconstructed force and directly measured arc force. Their difference is the non-arc forces.
the non-arc forces in the pool.

The present work is the first time to report directly and quantitatively obtained distributions of surface tension and gravitational pressures. These findings are important to the understanding of the mechanisms of pool cavity formation.
6.4 INVESTIGATION OF RELATION BETWEEN POOL DEPRESSION AND WELD GEOMETRY

In this section the relation between pool depression and weld penetration is discussed. In order to simulate a weld in progress and to have a fully developed pool surface depression, the welding time was selected to be about three seconds on a stationary GTA weld. Various current levels were systematically tested with 4 mm torch-to-workpiece distance.

Figures 81 and 82 show the results for measured maximum depth of pool depression and maximum depth and width of weld penetration versus welding current squared. In Figure 81 the separation between the two curves represents the thickness of the liquid layer. Depth/width ratios of the weld and the pool depression are shown in Figure 83. The relation between pool depression and weld penetration, which is important to weld penetration control, is shown in Figure 84.

In Figure 81 weld penetration in three regions of current can be seen. Each region demonstrates a different dominating weld penetration mechanism. In the first region, at low current, below approximately 100 A and with a small amount of liquid at the pool bottom, the base metal is exposed more directly to the extremely high temperature of the welding arc plasma than is a pool with more liquid.
Fig. 81—Relation between the depth of the pool depression and the depth of the weld penetration on low carbon steel for stationary gas-tungsten-arc weld. A similar behavior of weld penetration in regions I and II was also found in the same current range in a study of weld penetration [79,87].
Fig. 82- Relation between the width of the weld penetration and current squared.
Fig. 83—Relation between aspect ratios of pool depression and weld penetration on low carbon steel and current squared. While pool depression exists, weld aspect ratio increases.
Fig. 84- Relation between weld penetration and pool depression depth. Diagonal solid line corresponds to equality between pool depression depth and weld penetration.
Because direct arc heating increases as current increases, a sharper increase of weld penetration was found in region I than in region II where conduction and convection are the dominating mechanisms. In addition, because of the low level of current in region II the weld penetration is small, less than about 1.5 mm. A similar sharp increase of weld penetration was also found in the same current range in a study of weld penetration [79].

While a liquid layer exists and acts as an insulator between the welding arc and the workpiece, the heating of the base metal by conduction and convection is relatively slow compared to direct arc heating. Therefore the weld penetration increases only slightly. This is region II as shown in Figure 81 at currents between 100 A and 200 A. A similar slow increase of weld penetration was also found in the same current range in [79,87].

As the current increases further, because the stronger arc plasma jet pushes the liquid metal to the side, the pool is depressed and the base metal at the pool bottom is more directly exposed to direct arc heating similar to region I. Therefore a more rapid increase of weld penetration was found which is region III in Figure 81 where a steeper slope of weld penetration than in region II can be seen. As the current increases further, the liquid layer becomes thinner, becoming less than about 0.5 mm at currents above 300 A.
Partly because the arc plasma jet becomes more concentrated at high current as discussed above, the increase of weld width in region III is slower, as shown in Figure 81.

In [79], weld penetration at currents above 250 A, and thus the effects of pool depression on weld penetration, was not investigated. Four distinct current ranges for the depth of penetration in travelling steel welds were found by Chihoski [87]. In his study the penetration shows a similar slow increase with current in the 100-200 A range, followed by a similar steep increase with current in the 200-300 A range. The 300-400 A range shows almost no response of current to penetration and in the 450-600 A range, penetration begins to increase moderately with current.

In addition to current, other welding parameters such as electrode tip angle, arc voltage, and welding speed can affect the shape of the curves and the liquid layer thickness as shown in Figure 81. For example, at high welding speed there is short heating time at any particular location on the weld and so the liquid layer is likely to be thinner than for stationary welding (or even nonexistent). Therefore the base metal at the pool bottom is more likely to be exposed to the direct arc heating. Thus the liquid layer between the two curves in Figure 81 should be thinner and region II should be narrower. Although three distinct regions of weld penetration have been found, data of weld
width do not show such distinct as shown in Figure 82. The quite smooth relation between weld width and current is partly due to effect of the pool convection.

The effect of pool depression at high current on the weld shape (depth/width ratio) becomes clearer as shown in Figure 83. In Figure 83 in the low current range from 100 A to 250 A, i.e. before the pool is significantly depressed, the weld depth/width ratio can be seen to decrease as the current increases. This is because, as the current increases, the welding arc expands, hence the weld width expands. Note that the increase of weld depth is slow in this current range (region II in Figure 81). In addition, the outward pool surface flow driven by the negative surface tension gradient [19] also contributes to the increase of the weld depth/width ratio. In a recent experimental study of weld shape [23], a similar value (about 0.2) and decrease of weld depth/width ratio with increasing current was found in the same current range. In [23], no investigation of weld penetration at currents above 250 A was reported.

In Figure 83, as the current increases above about 250 A, the effect of pool depression on the increase of the weld depth/width ratio can be clearly seen. This is simply because the liquid metal is partly pushed aside by the arc plasma jet and the underlying base metal is more directly exposed to the direct arc plasma heating, leading to a
deeper weld penetration.

Figure 84 shows the relation between weld penetration and pool depression. The diagonal solid line corresponds to equality between pool depression and weld penetration. The separation between this line and the loci of experimental points represents the thickness of the liquid layer which is the same liquid layer thickness as shown in Figure 81. It can be seen in Figure 84 that the depth of weld penetration asymptotically approaches the depth of pool depression as the current increases and the liquid layer at the pool bottom becomes thinner. The pool depression-weld penetration relation should be even closer for travelling arc welding because the liquid layer is thinner.

Pool depression at high current and welding speed is certainly the dominant mechanism in weld penetration. It is important that pool depression and weld penetration are closely related; this provides the basis for weld penetration control in the next chapter, which depends on regulation of pool depression.

Pool convection is another important factor which may affect the shape of the weld and the stability of the depressed pool surface. For a flat pool, simple inward or outward surface flows (depending on the surface tension gradient) and their effects on weld shape have been studied in [19,23]. For a depressed pool with heat flux distribution
similar to the current density distribution [24], the pool surface in the hump region should have the lowest surface tension because the temperature is highest there. Therefore, surface flows driven by the surface tension gradient may occur from the hump to the center and the boundary. In a computer simulation by Choo et al [24], different pool convection patterns were found at different pool depths and current levels. At low current with shallow depression, pool convection with one circulation was found. As current increases, the depressed pool surface becomes deeper and more complicated pool convection patterns were found with three circulations at different depths in the pool. The effect of the shape of the pool depression on pool surface flow and internal pool convection is clear.

Since the mechanisms of weld formation at high current are much different and more complicated than those of weld formation at low current, the algorithms for weld penetration control at high current need to be modified. Similarly, mechanisms of discontinuity formation at high current may also be related to the formation and stability of the depressed pool surface which is of great interest to weld quality control. In the next chapter, a new weld penetration control algorithm based on information on pool depression integrated with in-process weld quality inspection will be studied.
Table 6: Chemical compositions of low carbon steel and 304 stainless steel.

<table>
<thead>
<tr>
<th>Elements</th>
<th>LCS Weight %</th>
<th>SS304 Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>.26</td>
<td>.05</td>
</tr>
<tr>
<td>Mn</td>
<td>.65</td>
<td>1.6</td>
</tr>
<tr>
<td>P</td>
<td>.021</td>
<td>.024</td>
</tr>
<tr>
<td>S</td>
<td>.043</td>
<td>.025</td>
</tr>
<tr>
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<td>Cu</td>
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<td>.20</td>
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<td>.011</td>
</tr>
<tr>
<td>Ni</td>
<td>.12</td>
<td>8.8</td>
</tr>
<tr>
<td>Cr</td>
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<td>17.9</td>
</tr>
<tr>
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<td>.20</td>
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<td>.009</td>
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<tr>
<td>V</td>
<td>.000</td>
<td>.08</td>
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<tr>
<td>Nb</td>
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<td>Zr</td>
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<td>Ti</td>
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<td>.0006</td>
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</table>
6.5 DYNAMIC ARC-POOL INTERACTION AND POROSITY FORMATION

From the standpoint of weld quality control, improving the understanding of the stability of the depressed pool surface and the liquid metal fill-back into the depression cavity during solidification is as important as studying weld penetration. A complete study of weld formation should include these two aspects. Liquid metal fill-back usually occurs when the arc pressure is reduced due to torch movement or current reduction. In most sensor-based weld process control, only the stage of fusion was considered and the fill-back of liquid at the solidification stage was either ignored or left without control. Mechanisms of weld discontinuity can be even more complicated than mechanisms of pool depression since the latter is only a part of the former.

To improve the understanding of weld formation, pool formation has been studied further on low carbon steel and 304 stainless steel. A longer welding time than that used previously in the study of weld penetration was used to investigate the dynamics of the arc-pool interaction. Table 6 presents their chemical compositions and special attention was given to elements affecting the surface tension [19,23,35].

Figure 85 shows a sequence of 26 image windows obtained
Fig. 85- Sequence of 26 image windows showing change of the low carbon steel pool depression and weld pool size. Welding time was 12 seconds. Last two columns show pore formation accompanied by pool instability and transition to chaos.
by real-time radiography during welding on low carbon steel at a fixed torch-to-workpiece distance 4 mm. For each window, the maximum depression depth of each pool is marked by cross lines. The sequence starts from the window at the upper left corner of the image (window #1) which is at the beginning of welding. Window #26, which is at the end of welding, is at the upper right corner. Each window has the size 12.3 x 17.6 mm (56 x 80 pixels). The dark semicircle at the left of each window is the shadow of the welding electrode. The total welding time was twelve seconds. The radiographic images here shown were taken at intervals of approximately 0.46 seconds. The welding current was set constant at 300 A. The brightness range of the images has been expanded to increase the image contrast.

The measured maximum depression depth of each pool image, by reconstructing pool depression for each window in Figure 85, and the measured arc force are shown in Figure 86. The reconstructed pool depression profiles shown in Figure 87 (1) through (9) correspond to windows #1 to #9 in Figure 85 where the gradual increase of pool depression in time can be clearly seen.

As may be seen in the beginning (windows #1 to #9) the pool depression depth (brightness) and size (diameter of white circle) increase in time. Pool depression reaches a steady value at about three to four seconds which
Fig. 86- Measured maximum depth of the depressed steel pool surface and force versus time on low carbon steel at a fixed torch-to-workpiece distance 4 mm. The dynamic change of the depressed pool surface is also shown.
Fig. 87—A sequence of cross-sectional profiles of the growing depressed pool surface measured from 0 to 3.84 seconds on low carbon steel at torch-to-workpiece distance 4 mm and current 300 A.
corresponds to window #9. A similar response time for pool depression was found in [53]. In the interval from window #10 to #17, the pool depression remains approximately constant (also shown in Figure 86 from about four to eight seconds).

An important phenomenon starts at about the eighth second, window #18. The porosity appearing in the pool is visible as a small white spot. From this moment the welding pool begins to lose its stability, leading to chaos. The chaotic movement of pores is dominant, instead of a stable depressed pool. Note that during pore formation the location of maximum pool depression, affected by pool motion, is not necessarily in front of but around the electrode. Figure 88 shows the weld cross-section after welding with some pores visible. This phenomenon of porosity formation was repeatedly observed at different currents.

Figure 89 shows a sequence of 28 images of the SS304 pool which was taken by a procedure similar to that for the low carbon steel (Figure 85). Measured pool depression and arc force versus welding time is shown in Figure 90. In Figure 89, a stable pool and no porosity are seen. After the weld solidified, no porosity was found from X-ray images and metallographs. Pool depression measured for SS304 has a similar value, about 2.5 mm, as that for low carbon steel (Figure 86). The arc force measured for SS304 at 300 A was
Fig. 88- Metallography of weld crosssection with several pores seen.
Fig. 89—Sequence of 28 image windows showing change of the SS 304 pool depression and weld pool size. No pore formation was observed.
Fig. 90 - Measured maximum depth of the depressed SS 304 pool surface and force versus time measured at a fixed torch-to-workpiece distance 4 mm.
found to be about 0.72 gram which is similar to the arc force measured on low carbon steel at the same current, within ± 0.05 gram. The difference of total measured force as shown in Figure 86 and 90 is due to the electromagnetic forces acting on different areas.

There are several varieties of pores in welds and several mechanisms may be involved [43,46]. Nucleation of porosities in the pool may be initiated by chemical reaction of components and gas desorption. In a series study of porosity [45], weld porosity was found to increase exponentially with the amount of carbon in the base metal. Low carbon steel has about five times more carbon than SS304, as shown in Table 6. In addition, the higher amount of deoxidizers such as Si and Al in SS304 may decrease the oxygen in the pool, therefore reducing porosity. Probably small gas bubbles were initiated in the pool later rising to the surface due to buoyancy. Loss of local stability may be due to porosity formation and local liquid vortices inside the pool [24]. Subsequently more porosities were trapped in the weld. In [53], a similar entrapment of gas bubbles, formed by suddenly extinguishing the arc after a deep pool depression was formed, was found by weld metallography. Gas desorption, which often occurs during solidification due to lower gas absorption in the solid than in the liquid, may not be the mechanism here since the porosity occurs during
melting.

The arc force was observed simultaneously with pool formation. It can be seen in Figure 86 that the measured force reaches a steady value within 1.5 seconds and the pool depression reaches a steady value in about three to four seconds. No observable change of the measured force was found after the force became steady and before the pool depression reached a steady value. This means that while the pool depression was increasing, no significant change of the measured force was observed. In other words, change of the pool surface shape has no observable effect on the measured force. Figure 86 also shows that no similar oscillation of the arc force was observed while the pool surface oscillated and no oscillation of the arc voltage was observed while the pool oscillated. In Figure 90 for SS304, the pool depression is approximately constant between 2 mm and 2.5 mm after reaching a steady value at about 3 seconds. A slight increase of the total measured force was occasionally observed as shown in Figure 86. Its causes are not completely understood at this stage.

The above observation of the arc force and the dynamic pool depression opposes the view that the shape of the depressed pool surface may significantly affect the arc force due to current density redistribution. It seems that the distribution of the arc plasma pressure continues to
vary while the total arc force stays about the same. Although the mechanisms of porosity formation and the effect of the pool shape on the total arc force are not completely understood, the unique capability of the technique developed in this study to observe and study discontinuity formation in the welding pool is clear. The information about pool depression obtained in this work is also important for weld penetration control based on pool depression.

6.6 SUMMARY

In this work, simultaneous measurements of the welding pool depression using radiography and the arc force using a force sensor were performed in a stationary non-consumable arc welding process to study the dynamic arc-pool interaction. Graphical relations between welding current, arc force, maximum pool depression depth, and maximum weld penetration depth were established.

A linear relation between weld arc force and current squared is found. A linear dependence of pool depression on current squared is found. The pool surface begins to be depressed at currents about 200 A. The depression width increases relatively rapidly at low current and saturates at high current. Three distinct current ranges for the depth of weld penetration were found. While pool depression exists,
the weld aspect ratio increases.

Distribution of surface tension and gravitational pressures were calculated based on the information of pool surface topology and material surface tension and density. Dynamic arc-pool interactions and the stability of the depressed pool surface have been investigated during welding. Weld porosities have been observed for the first time during welding. This is the first time a better picture of the welding process at high current (with pool depression) has been obtained.
CHAPTER VII

RADIOGRAPHIC SENSING AND CONTROL
OF WELD QUALITY

In this chapter, the feasibility of three approaches of weld quality control based on in-process radiographic information of weld and pool will be studied. The first approach is based on the information extracted from real-time radiographic images on weld quality, the second is based on the direct information on weld pool depression, and the third is based on the information on both pool depression and weld penetration.

7.1 EXPERIMENTAL PROCEDURE

The schematic diagram of real-time weld quality control is shown in Figure 39. Real-time radiography is essentially used as a vision system for measuring the weld pool and the weld. The image from the image intensifier is fed to the digital image processor, where the image is digitized and analyzed in real time. Specific features are extracted from
the image and decisions on weld quality are made (for example complete or incomplete weld penetration). Real-time radiographic images were received by the television camera and digitized at a rate of 30 frames per second.

To control the welding power supply, the dial potentiometer used for manual remote control was replaced by a voltage-controlled potentiometer. This potentiometer was integrated on a PC board controlled through a D/A converter by computer. The current and the voltage from the welding power supply were fed through a signal conditioning and isolation board to the computer. The signals were digitized by using a 12-bit A/D converter. In addition voltage and current were registered by the strip-chart recorder. In the computer the current and voltage were smoothed to extract the DC component.

The experiments were performed on welds made in the flat position by using the mechanized submerged arc welding (SAW) process. The weld was simultaneously monitored or controlled with the real-time radiography system. Prior to welding, the welding flux was placed at the top and bottom of the base metal. All the samples were prepared from 356 x 50 x 6.35 mm (14 x 2 x .25 inch) mild steel. The welding wire was a continuous bare steel electrode 2.38 mm (3/32 inch) in diameter. A granular compound with a density of about 1.38 g/cm³ was used as the welding flux. The density
of the welding slag, which is melted and resolidified flux, was about 2.89 g/cm³.

Complete weld penetration was required in this series of experiments. For the first approach, the width and thickness of the weld reinforcement and the depth of weld penetration were measured and compared with radiographic data. For the second approach, the depth of pool depression was determined from the radiographic images. To determine the actual weld penetration, the welds were sectioned after welding.

During the experiments, the radiographic exposure was initiated prior to welding to adjust the radiographic parameters (tube voltage and current) for optimal contrast. After the tube parameters were set, the welding was begun and radiographic images of the welding process were observed and recorded.

7.2 WELD QUALITY CONTROL BASED ON INFORMATION ON DISCONTINUITIES EXTRACTED FROM RADIOGRAPHIC IMAGES

Change of welding conditions such as current, voltage and/or speed of welding can affect the thickness and width of the weld reinforcement and penetration. In addition, these parameters influence the existence and degree of
incomplete weld penetration. Incomplete penetration lowers the weld bearing capacity, and hence is considered a weld discontinuity. From the weld cross section, dimensions of both the welding reinforcement and the inadequate joint penetration were actually measured. They were compared with the calculated values determined from the real-time radiographic images.

7.2.1 Manual Remote Control of Submerged Arc Weld Penetration

An example of a frozen image (one frame) from sequences of real-time radiographic images taken during submerged-arc welding is shown in Figure 32. As discussed previously, the base metal, weld, lack of penetration and melted pool are seen in the image. To establish a relationship between a gray level value of a pixel and the actual thickness of the material, the transfer function of the complete measuring system was determined by taking radiographic images of steel plates with slots of various depths and shims of various thicknesses. Steel plates of the same thickness as the base metal of the weldments were used. The slots simulate insufficient weld penetration and the shims simulate weld reinforcements.

The results of the measurements are summarized in
Figure 91, where the logarithm of the normalized value of the gray level is plotted versus slot depth or shim thickness, which are given in the deviations, $\Delta h$, from the original plate thickness, $h$. $B_2$ represents the value of the gray level in the images of the slot or shim, and $B_1$ is the gray level in the image of the plate. The straight line in Figure 91 is the least square fit of the experimental data.

An example of data from a real-time radiographic image is shown in Figure 92. The points corresponding to the weld reinforcement are in the upper part of the figure (increasing thickness) and the data for incomplete penetration are in the lower part of the figure (decreasing thickness). The straight line in Figure 92 is the least square fit of the experimental data from Figure 91 (sample with slot and shims). The data from the actual weld are quite well fitted by this calibration curve. This example illustrates that the depth of weld penetration and thickness of weld reinforcement may easily be measured in real time.

Visual observation of real-time radiographic images and the information on the existence of lack of penetration received from these images were used for manual weld penetration control. The welding current was manually adjusted in such a way that the full penetration occurred. A typical example of the results of such an experiment is summarized in Figure 93. Image profiles, in the middle
Fig. 91- Logarithm of the normalized gray level value versus slot depth and shim thickness ($\Delta h$).
Fig. 92- Logarithm of the normalized gray level versus weld penetration and reinforcement ($\Delta h$) for actual weldments. The straight line is the least square fit of the experimental data from Figure 91.
Fig. 93—Example illustrating manual process control. Using information received from radiographic image, the welding current is readjusted in such a way that full penetration occurs.
portion of Figure 93, show the changes of the values of the gray levels along a particular horizontal line of the digitized image. The deep, wide minimum of the profile corresponds to the increased thickness of the weld due to weld reinforcement. Units for the horizontal position in the image profiles are in pixels. One pixel is 0.2 mm for the selected field of view.

The lower part of the figure shows the metallographs of the weld cross sections corresponding to the image profiles in the middle part. At a welding current of about 390 A, full weld penetration is observed. This follows from the image profile and is supported by the metallograph of the weld cross section, both shown in the right column. When the current is reduced to 340 A, there is incomplete weld penetration, indicated by the peak A on the center image profile. The depth of the weld penetration was calculated from the height of this peak as discussed earlier. The information on incomplete weld penetration can be extracted from the appearance and height of peak A by computer. When incomplete penetration occurs, the welding current was increased as illustrated in the left column of Figure 93. When the current is increased above 360 A, the peak A disappears indicating a full penetration, as is shown in the corresponding weld cross section.
7.2.2 Processing of Data and Outline of Algorithm for Computer Control of Weld Penetration

As was discussed in the previous section the information on lack of weld penetration, which is visible as a bright line in Figure 32, may be extracted from the shape of the pixel value (brightness profile, Figure 93). In this section an on-line computerized decision-making process for this feature is described. The difficulties of doing this lie in requirements for high-speed processing and noise reduction.

Brightness profiles were analyzed from the image at a distance of about 25 mm (1 inch) behind the welding torch to avoid the molten area which is "noisy" due to pool oscillations. This distance may be small enough for a quick response on the weld quality and for corrections. One of the problems revealed in this early stage of the development was a high noise level in the profile traces. The noise complicates the finding of the profile maximum (Figure 93) which should be done automatically by computer.

To reduce the noise level, significant space averaging and smoothing (low-pass filter) were done. First, four consecutive TV raster lines (Figure 94) were digitized and averaged. The width of the digitized lines (window) was 120 pixels which is equivalent to a line width about 23 mm (0.91
Fig. 94—Schematic diagram of the weld image showing the position of the window for image analysis.
inch) across the weld. The sequence of averaging and smoothing is illustrated in Figure 95 where the solid points correspond to one line of pixels (middle row in Figure 95). Second, five neighboring pixels were averaged with the smoothed profile shown by the lowest line of 20 pixels in Figure 95.

The profile represents smoothed brightness changes through the weld image. An example of such a profile in the part of the weld lack of penetration is shown in Figure 96 (A). The value $B_0$ corresponds to an increase of weld thickness relative to the base metal area. The brightness $B_1$ characterizes the value of the lack of penetration. The value of the ratio $B_1/B_0$ is taken as one of the criteria for computer recognition of lack of weld penetration. It is compared to the threshold level which is determined by the value of background noise. Full penetration occurs when $B_1/B_0$ is less than the threshold level. A typical image profile for complete weld penetration, after the above averaging procedure, is shown in Figure 96 (B).

The second criterion selected for determination of weld penetration is based on the ratio of the area of the cross sections $A_1$ and $A_0$ as shown schematically in Figure 97. This value characterizes the cross-sectional area of the lack of weld penetration. Based on these data, the thickness and width of weld reinforcement, and depth and width of lack of
Location of pixels

1 2 3 4 5 6 7 120
• • • • • • •

• • • • • • • Four windowed, digitized
raster lines, 120 pixels in length.

sum

1 2 3 4 5 6 7 120

Averaging and data compression

Final smoothed weld profile.

20 pixels in length.

Fig. 95—Schematic diagram showing pixel arrangement in the window and the order of data smoothing and compression.
Fig. 96- Brightness profile across the image of the weld. $B_0$ is the difference in brightness levels between base metal and weld reinforcement. $B_1$ is the brightness difference between brightness levels of complete and incomplete penetration.
Fig. 97- Schematic showing the cross-sectional area of profiles taken into account in the second weld penetration criterion (area ratio).
weld penetration may be calculated from the radiographic image. Both the amplitude and the area criteria give information on depth and width of lack of weld penetration.

The algorithms for decisions on the depth of penetration are schematically outlined in Figure 98. The threshold levels were set either by radiographically examining previously made fully penetrated and incompletely penetrated welds or by calculation from the brightness-thickness ratio and pixel size. In this experiment, the threshold values were set to 0.1 for the brightness ratio, 18 mm$^2$ for the minimum reinforcement area and 0.1 for the area ratio. When any one of the above criteria was fulfilled, the weld penetration was judged incomplete.

7.2.3 Computer Control of Weld Penetration

The main distinguishing feature of the system is that information on weld quality extracted from radiographic images is used in feedback for welding power supply control. Therefore, the first part of the system to be checked is the stability and effectiveness of the algorithm for measuring weld penetration. This was done by analyzing images recorded on a VCR during a typical experiment on monitoring weld penetration, described in the previous section. The results of the decision on complete or incomplete
Fig. 98- Outline of the algorithm for deciding on weld penetration.
penetration, done by the computer program, were superimposed on the recorded image and may be observed by the experimenter.

Thus, the validity of the computer decision may be compared with the visual perception of the operator. In such a way, the algorithm was debugged and the correctness of the threshold levels in its decision-making was checked. This is illustrated in Figure 99 where the weld image is shown together with an overlay of the computer decision. In Figure 99 (A), where the penetration is visibly incomplete, the computer decision is shown as "incomplete," as highlighted by a white box. Figure 99 (B) represents complete weld penetration. The decisions were based on a profile distribution taken along the white line shown across the weld.

The channels for measuring current and voltage were checked independently. Difficulties arose due to large random changes of current. In addition, signal filtering and smoothing was not a trivial problem. The effectiveness of the computer control of the power supply was studied separately.

To demonstrate the capability of the complete system, the following approach was taken. It was decided to force the system into the region of incomplete weld penetration and afterwards to lock it on automatic control and observe
Fig. 99- Real-time radiographic image and computer decision overlay. Computer decision (a) "incomplete" (highlighted by white box) or (b) "complete".
its recovery to the region of full penetration. For this purpose, in the initial stage of welding, the change of welding current was preprogrammed in the computer. Welding started in normal conditions. Then, the computer decreased the current and when an indication was received from image analysis of incomplete weld penetration, the feedback locked on and the computer began to increase the current in the power supply until the message "full penetration" was received.

Figure 100 illustrates the signal that controls the welding current, the actual measured welding current and a photograph of the weld sample with both top and bottom views. The welding current started at about 385 A (the command signal was 0.7 V), the welding voltage was about 30 V and the welding speed 5 mm/sec (12 in/min). Shortly after starting the welding arc, the welding current was rapidly decreased to about 350 A (command signal was about 0.55 V) to obtain simulated lack of penetration. The feedback welding current command signal was increased by 0.05 V (roughly about 10 A in current) with each detection of lack of penetration until full weld penetration was obtained.

Figure 101 in the bottom row shows three typical cross sections of the weld sample. In the top row the corresponding brightness profiles of the image are shown. The decision on weld penetration was made by analyzing these
Fig. 100- Example showing (A) Signal that controls welding current. (B) Actual measured welding current. (C) Photograph of weld sample (top and bottom view).
Fig. 101- Example showing (A) Brightness profiles of images with computer decision "complete" (left and right) and "incomplete" (middle). (B) Corresponding photographs of weld cross sections.
profiles as discussed earlier. Cross Section No. 85, a full penetration weld, was taken shortly after starting the welding with welding current about 385 A. Cross Section No. 106 was at the point where the lack of weld penetration was detected with welding current about 350 A. Cross Section No. 124, a full penetration weld again, was the weld cross section after welding current increased. The actual data for the above mentioned points with which the decision algorithm operated are summarized in Table 7, where brightness ratios, area, area ratio and the predetermined threshold values are given.

Because of noise in the radiographic images, the threshold values of area, area ratio and brightness ratio are important in detecting weld quality by this method. They are related to the detectability of a radiographic system as discussed previously. To have optimal control of weld quality, they must be selected carefully. It will be difficult to detect a small lack of penetration using a very high threshold value. But, a very low threshold will make the penetration control system very sensitive to radiographic noise. Several carefully controlled trial tests of weld penetration were needed to determine these threshold values.

As previously discussed, the system unsharpness value is another important factor in addition to the noise level
in detecting small discontinuities. When lack of penetration is very narrow and similar to or less than the system unsharpness value, the system unsharpness becomes vital. This is especially important for a weld joint with a narrow gap. The linear compression of weld profiles may also decrease the resolution of the weld discontinuities although it increases the processing speed.

The window of the image was selected at a distance (25 mm for the above case) behind the welding torch to avoid the "noisy" weld pool region. At this distance, the weld may be near to solidification. The effect of increasing welding current may not be able to recover the weld penetration although it may decrease the lack of penetration. A closer distance will help to give better control of weld penetration but the effect of the noise from weld pool motions and gas bubbles must be considered.
Table 7. Measured area, area ratio and brightness ratio.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Area</th>
<th>Area Ratio</th>
<th>Brightness Ratio</th>
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<td>(1)</td>
<td>(2)</td>
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<td>threshold</td>
<td>400</td>
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<td>#85</td>
<td>543</td>
<td>24</td>
<td>23.2 --</td>
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<tr>
<td>#106</td>
<td>590</td>
<td>24</td>
<td>25.7 41 0.065</td>
</tr>
<tr>
<td>#124</td>
<td>700</td>
<td>32.8</td>
<td>26.7 --</td>
</tr>
</tbody>
</table>

Column 1 shows area in threshold level pixel.
Column 2 shows calculated area from data in Column 1 in mm².
Column 3 shows actual measured area in weld cross section in mm².
7.3 RELATION BETWEEN WELD PENETRATION AND WELD POOL DIMENSIONS BUTT-JOINT SUBMERGED ARC WELD

A weld made on a joint which has to be filled by liquid metal during welding is more complicated than a bead-on-plate weld. Knowledge of relations between weld penetration and pool dimensions for butt-joint weld are required in order to use the information on the weld pool to the control weld penetration.

The dimensions of the depressed pool surface of the butt weld were monitored by using the real-time radiographic system described as discussed previously. Using different welding currents and joint gaps, the resulting weld penetrations were changed. A greater welding current resulted in a larger pool diameter and full weld penetration.

Examples of two three-dimensional radiographic images are shown in Figure 102. Light areas correspond to reduced thickness of the material and peaks are images of the depressed pool. The brightness of the weld pool area means that molten metal was pushed by plasma pressure away from the electrode which is also visible in these images. When the welding current is insufficient, melting of the base metal is less intense and the light area becomes narrower (Figure 102 (A)). In Figure 102 (A), lack of weld
Fig. 102 - Three dimensional image of the depressed pool for submerged-arc butt weld. (A) Partially penetrated weld with lack of penetration shown. (B) Fully penetrated weld.
penetration also can be seen in the solidified area behind the pool as a white stripe (it is indicated by an arrow in the figure). A butt weld with lack of weld penetration shows the pool diameter to be approximately the width of the butt weld gap.

In Figure 103, radiographic images (top) taken in the vicinity of the weld pool and metallographs of the corresponding weld cross sections for full and partially penetrated welds are shown. The computer profiles (tracings) of the 3-D digitized images (Figure 102) from the middle of the pool are shown. These may be used for quantitative measurement of the pool dimensions by the computer. Weld cross sections (Figure 103 (c)) clearly show that the left weld has a lack of penetration.

The results of the experiments are summarized in Figure 104. In Figure 104, the root width "W", lack of weld penetration (-h), and the thickness of root penetration (+h) of the welds measured from metallographic cross sections are plotted against depressed pool diameter measured from radiographs.

The relationship between pool diameter and weld penetration for butt-joint weld has shown promising results. This method can be used to control weld reinforcement and penetration at the position immediately behind the weld electrode eliminating delay in the control of the weld
Fig. 103- Example showing (A) Two real time radiographic images of the pool depression for complete (right) and incomplete (left) weld. (B) Computer profile of brightness level through the middle of pool. (Unit for the horizontal position is in pixels. One pixel is 0.2 mm for the selected field of view.) (C) Metallographs of the corresponding butt weld cross sections showing complete (right) and incomplete (left) butt welds.
Fig. 104- Results of (A) Root width "W" and (B) penetration depth "h" of butt weld obtained from cross sections versus depressed pool diameter measured from real-time radiographic images.
penetration. Conceptually, it is more effective to ensure the reinforcement of a weld and prevent incompleteness of weld penetration than to change welding parameters to their proper values after lack of penetration occurs.

7.4 WELD PROCESS CONTROL WITH FEEDBACK ON WELD POOL DEPRESSION

7.4.1 Relation between Radiographic Image of the Pool and Value of Weld Penetration

An example of one frame from a sequence of radiographic images of a molten pool of a bead-on-plate weld taken during submerged arc welding is shown in Figure 105. The image is positive, so a thinner section of the depressed weld pool is represented by a lighter area. The welding torch and welding electrode are seen in the bottom of the image and the circular white area in front of the welding torch is a weld pool. The solidified weld and the molten pool are covered by the unfused flux and by the slag. However, the slag has little effect on the image because of its low density. The gray area surrounding the weld is the base metal. The image in Figure 105 was taken on a 6.35 mm (0.25 in) thick steel plate using 150 KV and 10 Ma on the X-ray tube.
Fig. 105—An example showing one frame of the real-time radiographic image of bead-on-plate submerged-arc welding. X-ray tube voltage 150 KV, tube current 10 mA, welding arc current 410 A, arc voltage 30 V, welding speed 11 mm/sec.
The material thickness can be reconstructed from the image by knowing the brightness level and the X-ray attenuation coefficient. The relationship between the brightness level and the material thickness in this work was obtained experimentally. In this way, three-dimensional information on the weld pool was obtained that can be used to determine weld penetration.

Figure 106 is a schematic showing the consumable welding electrode, electric arc, metal transfer, depressed pool surface, liquid pool, weld penetration, and base metal. In Figure 106, "H" is the plate thickness and "d" the thickness of liquid and solid metal together at the bottom of the weld pool. Because of the heat of the arc that melts the plate and the arc pressure on the molten pool as discussed in the previous chapter, the weld pool is depressed during welding and the material thickness is reduced from "H" to "d." The depressed pool surface becomes deeper and wider when a higher welding current is used due to the expansion of the welding arc at higher current.

The information on the formation of the depressed pool (visible as a bright circular area in Figure 105) is extracted by converting the radiographic brightness profiles to cross-section profiles of the pool (Figure 107). High-speed processing is required to make the on-line computerized decision. Cross-section profiles of the
Fig. 106- Schematic illustration of welding electrode, metal transfer, depressed pool surface, and liquid-solid interface.
Fig. 107—Typical example of crosssection of depressed pool surface and solidified weld for submerged arc welding. Region between dots and solid line corresponds to the layer of liquid metal during welding.
depressed pool surface were analyzed from the image during welding. From the cross-section profile of the depressed pool surface and metallographic cross sections, the depth of the liquid metal in the pool was determined together with the weld penetration (Figure 107). For the welding currents and speeds used, the thickness of this liquid layer was determined to be less than 1 mm at the bottom of the pool.

Figure 108 (A) and (B) show the depressed pool surfaces of partial- and full-penetration welds. In Figure 108 (A), a depressed pool surface and a partial penetration weld are shown with a layer of liquid and a layer of solid metal. When a higher welding current is used, the depressed pool surface becomes deeper and hence there is a deeper weld penetration. Above a critical current, a full-penetration weld will eventually result (Figure 108 (B)). From radiographic images and welding conditions the thickness and width of the weld penetration may be calculated.

7.4.2 Algorithm for Weld Penetration Control

The algorithms for decision on the depth of weld penetration are schematically outlined in Figure 109. Profiles of depressed pool surfaces (Figure 105) were measured from radiographic images as explained in the previous section. The threshold brightness level was preset
Fig. 108- Schematic illustration of relation between depressed pool surface and weld penetration of (A) partially and (B) fully penetrated bead-on-plate weld.
Fig. 109- Outline of algorithm for decision on welding penetration based on depth and width of pool depression.
corresponding to the threshold depression of the pool, based on the experimentally measured transfer function of the system. The threshold width was selected at the level of the threshold depth. When both criteria, depression depth and width, were satisfied, the weld penetration was deemed complete; otherwise, partial weld penetration was assumed. In this way both partial and full penetration welds may be controlled.

To reduce computer time and memory requirements, only the data on pool depression in the radiographic image were processed and stored. The size of the image window was selected to cover the entire region of the depressed pool. For this particular application the size of the window was 10 by 6 mm (40 by 30 pixels). A decision on weld penetration was made about 6 times per second.

In the experiment on a bead-on-plate submerged arc weld, several threshold values were tested on a 6.35 mm (0.25 inch) thick steel plate. Throughout the entire series of experiments, threshold values for weld penetration were found to be about 4.3 mm (0.17 inch) for the depression depth and 1 mm for the depression width (width of 4 pixels). This is translated to the threshold level for brightness in the pool image, which is 100 brightness level units (255 units is full scale). Selection of threshold values and accuracy of weld penetration control depend on radiographic
parameters and welding conditions.

7.4.3 Computer Control of Bead-on-Plate Weld Penetration

The main distinguishing feature of this system is that information on molten pool depression, extracted from radiographic images, is used in feedback for welding power source control. In the experiments on weld penetration control, the image processing procedure was automatically triggered after initiation of the welding arc. The location of the window was automatically determined by finding the highest gray level corresponding to the deepest pool depression. This is illustrated in Figure 110 (A) and (B) where the weld image is shown together with an overlay of the computer decision. In Figure 110 (A), where the depression is visibly darker (shallower pool depression) than in Figure 110 (B), the computer decision is shown to be partial penetration, as highlighted by a white box at the left of the pool. In Figure 110 (B), where the depression is visibly brighter (deeper pool depression), the computer decision is shown to be full penetration, as highlighted by a white box at the right of the pool. The decisions were based on profile distributions taken in the window between two horizontal lines across the weld (Figure 110 (A) and (B)).
Fig. 110—Real-time radiographic image of depressed pool and computer decision overlay. X-ray tube voltage 130 KV, tube current 10 mA, welding arc voltage 30 V, welding speed 11 mm/sec. (A) Partial penetration weld pool and computer decision "partial" indicated by white box at left of window. (B) Full penetration weld pool, I = 500 A, computer decision "full" indicated by white box at right of window.
For a fully penetrated weld the position of the maximum of measured pool depression is also located by two horizontal white lines and a vertical white line (Figure 110 (B) only). The intersection of the extensions of these lines is the location of the maximum measured pool depression. In this case, the true maximum pool depression is shielded by the electrode and is not available. This is partly the reason for choosing the depression width as the second criterion when making a decision on weld penetration.

To find a relationship between a gray level value of a pixel and the actual thickness of the material, the transfer function of the complete measuring system was determined by taking radiographic images of a steel plate with shims of various thicknesses. The welding flux was also added to better simulate welding conditions. The relationship between brightness level and material thickness depends on X-ray tube parameters and geometric configurations of the radiographic system.

To demonstrate the operation of the complete system, the following approach was taken. The weld was started with a low welding current to produce a partial-penetration weld. The system was then locked on automatic control and its recovery to the region of full penetration was observed. After the start of welding, the computer feedback locked on and began to increase current in the power source until full
penetration was achieved.

The welding current, measured maximum brightness and measured width of pool depression versus welding time are shown in Figure 111. The welding current (Figure 111) started at about 260 A with a welding voltage of about 30 V and welding speed of 11 mm/sec (26 in/min). The welding current was increased by roughly 6 A with each detection of partial weld penetration until full penetration was obtained. Pool depression width is measured at the threshold depression depth, 4.3 mm (0.17 inch) depth on a 6.35 mm (0.25 inch) thick plate in this case.

In the transition from partial penetration to full weld penetrations four regions of weld penetration were observed. In Figure 111, Regions I, II, III and IV correspond to a stable partial-penetration, an unstable full-penetration, an unstable partial-penetration and a stable full-penetration weld, respectively.

An unstable partial-penetration weld is a deep partial penetration weld but without root penetration. Such a penetration is more sensitive to pool dynamics and less tolerant to system disturbances than a stable partial penetration which may exist at a lower welding current. An unstable full penetration weld is characterized by small root penetration and, as in the case of an unstable partial penetration, is more sensitive to pool dynamics and less
Fig. 111- Welding current, measured maximum brightness, and measured width versus time.
tolerant to system disturbances than a stable full-penetration weld with greater root penetration (such stable full penetration may be achieved at a higher welding current). System disturbances may be due to erratic mechanical travel and wire feeding, fluctuations of the welding power source, and a nonuniform heat sink along the weld.

A sequence of 98 image windows which demonstrate the pool depression changes during welding process control is shown in Figure 112. The sequence starts from the image window at the top left corner in the Figure (Window #0) which is at the beginning of welding process control. Windows #0 to #33 correspond to the stable partial-penetration (region I in Figure 111), windows #34 to # 46 to the unstable full-penetration (region II in Figure 111), windows #47 to #63 to the unstable partial-penetration (region III in Figure 111), and windows #64 to #96 to the stable full-penetration (region IV in Figure 111). Window #97, which is at the end of welding, is at the right lower corner.

Photographs of the weld fragment from the top and the bottom views of the weld are shown in Figure 113 (welding was done from right to left). Regions II, III and IV in Figure 113 correspond to Regions II, III and IV in Figure 111, respectively. Region I, of stable partial penetration,
Fig. 112- A sequence of 98 image windows showing control of bead-on-plate weld pool depression. Radiographic parameters and welding conditions are the same as Figure 110.
Fig. 113- Photograph of fragment of the weld sample with both top and bottom views. The region of unstable full penetration is at the right, unstable partial penetration in the middle and stable full penetration at the left. The region of stable partial penetration is not shown.
is not shown in Figure 113. In Region II, at the right in Figure 113 (B), a weld with shallow root penetration is shown which is an unstable full-penetration weld. At the same welding current, depending on pool dynamics and system disturbances, the unstable full-penetration weld may transform to a partial-penetration weld as seen in the middle of Figure 113 (B). To overcome this unstable transition, the welding current is automatically increased after the unstable penetration is detected (Figure 111). By increasing the welding current, a full-penetration weld with deeper root penetration results, as shown in Region IV in Figure 111 and 113 (B).

Typical examples of fully and partially penetrated welding cross sections and corresponding brightness profiles are shown in Figure 114. The decision on weld penetration was made in real time by analyzing these profiles as discussed previously. The left of Figure 114 (A) shows the brightness profile of a partial-penetration weld whose cross section is shown in the left photograph of Figure 114 (B). In the right of Figure 114, a brightness profile of a full-penetration weld is shown (Figure 114 (A)) with its corresponding cross section. The partial penetration was produced at about 300 A welding current and the full penetration about 500 A.
Fig. 114—Example showing (A) Brightness profiles of pool image with computer decision: partial (left) and full (right). (B) corresponding photographs of bead-on-plate weld cross sections.
In addition, an electrode shadow in the right of Figure 114 (A) contains information on the position of the electrode. This information can be used in weld joint tracking to adjust the relative position between electrode and weld joint to make an acceptable weld.

In automatic welding, high welding current and speed are desirable to yield the highest productivity. In this case, the pool depression is greater than welding with low current and is easily observed by using this technique. Radiographic noise and system unsharpness do not cause problems in monitoring the weld pool. For a weld on a thin plate, a lower current (lower arc plasma force) is used and the depressed pool surface is shallow. For the low-current case, the radiographic signal of the pool depression is low and in the range of radiographic noise. As a result, the noise level becomes important and special image processing techniques are needed to extract accurate pool depression information. Welding at low speed is another extreme case. In this case, the liquid pool layer may be larger and the prediction of weld penetration from the depressed pool surface can become more complicated because of the pool motion.
Previously (the second approach) weld penetration was controlled by the use of radiographic information on weld pool depression to eliminate the time delay thus providing feedback before weld solidification. In that implementation the method was applied to control bead-on-plate weld penetration only which had no weld joint involved.

The main distinguishing feature of the present approach is that information on the molten pool and the weld quality extracted from radiographic images is used in feedback to control the welding process and to assure weld quality. As an example we consider results for submerged arc welding.

7.5.1 Processing of Radiographic Images for Lack of Weld Penetration

Radiographic weld penetration images are processed to locate and find the boundaries of weld reinforcement lack of penetration. This was done by taking the second derivative of the radiographic profile of the weld. Figure 115 (A) and (B) shows the brightness profile of the weld and its derivative for a partially and fully penetrated weld. It can be seen in Figure 115 (points A and B) that the second
Fig. 115- Cross-sectional brightness profile of weld and its second derivative.
derivative of the brightness profile is minimum at the boundaries of the weld reinforcement, which serves to locate the weld reinforcement. In Figure 115 (A) two maxima (points C and D) and another minimum (point E) of the second derivative can be seen which indicate the boundary and center of lack of penetration.

From information on the locations of weld reinforcement and lack of penetration and the weld brightness profile, criteria for weld penetration, \( \frac{B_i}{B_o} \), \( \frac{A_i}{A_o} \), and \( A_i \), were determined.

7.5.2 Processing of Radiographic Images of Butt-Joint Pool Depression and Weld Penetration

The functioning of the complete system was demonstrated as follows. The weld was started with a low welding current so only partial weld penetration occurred. Afterwards the system was locked on to automatic control and its transition to the state with full weld penetration was observed. After the system feedback locked on, the computer began to adjust the current output of the welding machine until the message "full penetration" was received.

The location of pool and weld windows are predetermined. This is illustrated in Figure 116 (A), (B), and (C) where the pool and weld images are shown together.
Fig. 116- Two-dimensional radiographic image of depressed pool and solidified weld with computer decisions overlaid. (A) Fully penetrated weld and partially penetrated pool. (B) Partially penetrated weld and fully penetrated pool. (C) Fully penetrated weld and fully penetrated pool.
with an overlay of the computer decision. Figure 116 (A) was taken at the beginning of welding, Figure 116 (B) at the transition region with increase of current, and Figure 116 (C) at the full penetration weld region which occurred after the transition with further increase of current.

7.5.3 Computer Control of Weld Quality

Figure 117 shows in the upper part the welding current and the pool depression width versus time. In the lower part the decision on the weld penetration obtained from the pool depression together with the decision on the weld penetration obtained from the solidified weld region are shown. The welding current (Figure 117) was initiated at about 375 A and then reduced to about 340 A in a few seconds. After welding current reduction, insufficient weld penetration occurred and the system control locked on. The computer starts to adjust the welding current by increasing it roughly 6 A with each detection of partial weld penetration until full penetration was obtained. The welding speed was 11 mm/sec.

In Figure 116 (A), the narrow pool depression is visible and its width is indicated by the distance between the vertical white lines in the front of the pool. The computer decision is partial penetration, as indicated by a
Fig. 117- At top: welding current and measured width of pool depression versus welding time. At bottom: decisions on weld penetration.
white box on the left of the pool. In Figure 116 (B) and (C), where the pool depression is visibly wider and its width is indicated by the distance between the two white lines in front of the pool, the computer decision is shown as full penetration, as indicated by a white box on the right of the pool.

Weld penetration decisions could also be made from weld image information. This is illustrated also in Figure 116 where the weld image is shown together with the computer decision. In Figure 116 (A), where the penetration is visibly complete, the computer decision is "complete" as indicated by the two vertical lines at weld boundaries. In Figure 116 (B), where the penetration is visibly incomplete, the computer decision is "incomplete" indicated by the three vertical white lines in the weld center. Two other vertical lines are shown indicating the weld boundaries. Figure 116 (C) represents complete weld penetration. The decisions were based on a profile distribution taken across the weld.

As shown in Figure 117 consistent decisions were made from the pool depression and the solidified weld images except in the transition region from a partial to a full penetration weld. The transition region is denoted by the letter "A" in Figure 117. The weld becomes partially penetrated immediately after the welding current reaches minimum so the computer decisions from both the pool image
and the weld image are "partial penetration". Next, the welding current was increased and full weld penetration was obtained as indicated by both decisions in Figure 117. The current was further increased in the transition region based on the "incomplete" indication from the pool image to assure stable full penetration. Stable full penetration is less sensitive to system disturbances and pool dynamics.

Both the pool depression width and depth on the image are used to make decisions on weld penetration. The width was measured at the level of the threshold depth (distance 'D') as shown in Figure 118. The threshold depth of pool depression is selected at a thickness which is close to the plate thickness. When the pool depression is less than the threshold depth, a partially penetrated pool is obtained as shown in Figure 118 (A). When the pool width measured at the threshold depth is greater than the threshold width (distance 'W'), a fully penetrated pool is obtained as shown in Figure 118 (B).

As shown in Figure 117, the weld is determined to be fully penetrated when the width of the pool depression is greater than the threshold width, or partially penetrated when the width of the pool depression is less than the threshold width. To reduce the influence of pool motion, the decision is made using two consecutive images. Pool depression width is measured at the threshold depression
Fig. 118- Schematic illustration of the threshold depth for weld penetration control. (A) Partially penetrated butt weld. (B) Fully penetrated butt weld.
depth, 4.3 mm on a 6.35 mm thick plate in this case. The threshold width is defined to be 22 pixels, and is 4.8 mm. A butt joint with a gap of about 3 mm was used which is greater than the unsharpness of the real-time radiographic system. Contrast sensitivity of the real-time radiographic system is the dominator factor in the detection of lack of penetration.

The decision on weld penetration from the weld image is based on analysis of the weld image profiles as discussed above. The results are shown in Figure 119. The weld is determined to be fully penetrated when both the brightness and area ratios are less than the threshold levels (see also below discussion of Figure 121 (B1)). At the beginning of welding as shown at left in Figure 119 the brightness ratio was found to be above the threshold brightness ratio because the current was low; thus the weld is determined to be a partial penetration weld. The threshold brightness and area ratios were set at 0.1. These criteria were chosen because the radiographic contrast sensitivity obtained by human visual perception for submerged arc welding is 4 %, remembering that machine perception using a simple algorithm is worse than human perception.

Photographs of a weld sample are shown in Figure 120. In Figure 120 (B), the small lack of penetration (left) caused by the decreased current can be seen at the left of
Fig. 119- Brightness and area ratios of lack of weld penetration together with the decision made on the weld penetration versus welding time.
Fig. 120- Photographs of weld sample. Welding was made from left to right. (A) top and (B) bottom view of weld.
weld. In the middle of Figure 120 (B) a transition region from partial to full penetration can be seen. On the right is the fully penetrated weld region.

A typical example of process control considering radiographic brightness profiles of a depressed pool surface from the pool image (left column) and the corresponding radiographic brightness profiles of the weld cross-section from the weld image (right column), obtained during welding, are shown in Figure 121. Metallographs of corresponding weld cross-sections made after welding are shown in Figure 122.

In Figure 121 (A1) (top row) the radiographic brightness profile of a depressed pool from a low current region (Figure 117) is shown. The radiographic brightness profile of the corresponding weld cross-section obtained from the weld image is shown in Figure 121 (B1) where a peak marked by the letter "A" can be seen indicating lack of weld penetration. Previously mentioned brightness and area ratios of lack of weld penetration are related to parameters of this peak. Its metallographic cross-section is shown in Figure 122 (A) where a lack of penetration weld can clearly be seen. Lack of penetration is due to small pool depression. The decisions made during welding from both pool and weld images are "lack of penetration" for this case.

The current increases under process control, resulting in the change of the pool depression image shown in Figure
Fig. 121- Brightness profiles of pool image and weld image: top row partial weld penetration and middle and bottom rows full weld penetration. The weld profile at the middle row corresponds to a weld without sufficient root reinforcement.
Fig. 122- Cross-sectional metallography of partially penetrated weld (top row) and fully penetrated weld (middle and bottom rows) corresponding to the profiles in Figure 121.
118 (A2) which is in the transition region from partial to full weld penetration. A radiographic brightness profile of the pool depression with greater width than the profile shown in Figure 121 (A1) can be seen. The radiographic brightness profile of the corresponding weld cross-section is shown in Figure 121 (B2) where no peak can be seen indicating a full penetration weld. Its metallographic cross-section is shown in Figure 122 (B) where a fully penetrated weld with a small root reinforcement is visible. Full weld penetration is due to medium pool depression as shown in Figure 121 (A2).

In Figure 121 (A3) a radiographic brightness profile of pool depression with large width can be seen resulting from further increase of current. The radiographic brightness profile of the corresponding weld cross-section is shown in Figure 121 (B3) where no peak can be seen indicating a full penetration weld. Its metallographic cross-section is shown in Figure 122 (C) where a fully penetrated weld is shown with a larger root reinforcement than the weld in the transition region (Figure 122 (B)). The decisions made during welding on both pool and weld images in this case are "full penetration".

Decisions on pool depression and weld penetration were made in real time by analyzing these profiles. The decision rate was about two times per second using a 16 Mhz IBM-AT
compatible computer without accelerating boards. The rate can be significantly increased if required.

To have high productivity in automatic welding high welding current and high speed are desirable. In this case, the pool depression is greater and is easily observed by this technique. Radiographic noise and system unsharpness do not cause problems in the monitoring of the weld pool. However, pool oscillation causes some uncertainty in making a decision. This is especially true when the pool diameter is close to the threshold width. For this reason control decisions were made using two consecutive images.
7.6 SUMMARY

It is a new trend to use nondestructive evaluation (NDE) techniques in welding process to improve weld quality. In this chapter the feasibility of using three different approaches of weld quality and penetration control has been demonstrated based on the information extracted from radiographic images of the weld pool and images of the solidifying weld. The major difference from other welding process control approaches is that closed-loop radiographic control is based on information directly related to weld quality and weld penetration. The use of in-process NDE technique may provide significant quality improvement and cost reduction.
CHAPTER VIII
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 CONCLUSIONS

In this dissertation the applicability and capability of real-time radiography for the sensing of weld pool formation and control of arc weld quality are studied and defined. The arc plasma-pool interaction at high current levels is studied to provide information needed for this purpose.

1) This work develops and evaluates a new technique for simultaneous measurement of weld pool depression by radiography and arc force by a balanced force measuring device. A floating electrical contact between the part and ground has been used to improve the force measurement. A linear relation between arc force and current squared is found, which is consistent with theoretical prediction. The precision of the pool depression measurements is about 0.2 mm. The effect of temperature related density change on radiographic measurement is found to be negligible by computer simulation of the radiographic images. Pool surface
geometry including humping on the pool periphery has been reconstructed. The volumes of the pool depression (empty space) and the hump area of the liquid metal around the pool are calculated separately and conservation of pool mass is verified. The thickness of the liquid layer between the arc plasma-liquid interface and the liquid-solid interface is determined by comparison of the pool depression with the weld penetration.

2) For quantitatively determining weld parameters from radiographic images, a systematic approach to analysis of a radiographic system by considering system characteristics such as resolution, sensitivity and detectability is here developed. It is shown that the above system characteristics may be found by measuring only two basic system parameters, such as unsharpness and contrast sensitivity. The detectability curve characterizes the image quality in the whole range of contrast and detail size and therefore is a better indicator of the radiographic image quality than conventional image quality indicators.

3) Experimental relations between welding current, arc force, maximum pool depression depth, and maximum weld penetration depth are established. A linear relation between weld arc force and current squared is found, as is linear dependence of pool depression on current squared. The pool surface begins to be depressed at currents of about 200 A.
The depression width increases relatively rapidly at low current and saturates at high current. The dependence of penetration depth on current is found to behave differently in three different current ranges, according to the arc heat transfer efficiency and the existence of pool depression.

The distributions of the surface tension and gravitational pressures are obtained from information on pool surface geometry and surface tension and density. Dynamic arc-pool interactions and the stability of the depressed pool surface have been investigated during welding. Weld porosity formation has been observed in the molten pool during welding. This shows the important capability of the method as a weld quality sensing tool.

4) The feasibility of using real-time radiography for real-time weld process and weld quality control has been studied. Information on weld penetration and pool depression extracted from real-time radiographic images and supplemented by sensor data on weld current and voltage is used for weld power supply control. The major difference from other methods of welding process control is that closed-loop radiographic control is based on information directly related to weld quality and weld penetration.
8.2 RECOMMENDATIONS FOR FUTURE WORK

The logical extension of this work is as follows:

**Arc-pool interaction:**

1. To compare the directly measured arc force and the balance forces calculated from the pool surface topography.
2. To analyze and measure surface tension forces by comparing theoretical and experimental results.
3. To continue studying stability of the depressed weld pool and discontinuity formation.
4. To describe pool depression phenomena in the region of transition from a partially to a fully penetrated weld pool.

**In-process control of weld quality:**

1. To study the relation between weld and pool dynamics for the earliest possible detection of weld quality.
2. To improve the detectability of weld discontinuities and the speed of image processing.
APPENDIX A

ANALYTICAL SOLUTION FOR ARC FORCE

The following derivation of the arc force for a conical arc comes from the electromagnetic interaction which produces the arc force and Converti's work [37] which includes the important effect of arc expansion. The arc force, generated by the electromagnetic interaction between the welding current and its self-generated magnetic field, is determined by the arc current distribution.

In [37] a current density distribution consisting of two components, axial \((J_z)\) and radial \((J_r)\), was assumed. For the axial component of a uniform axial current density, \(J_z\), the azimuthal magnetic field distribution, \(B_\theta\), is given in Equation 47 and the resulting radial magnetic pressure distribution, \(P_r\), due to the electromagnetic interaction between current and magnetic field is given in Equation 48.

\[
B_\theta(r) = \frac{\mu I}{\pi R^2} \frac{r^2}{2} \quad (47)
\]

\[
P_r(r) = J_z \times B_\theta = -\frac{\mu}{2} \left( \frac{I}{\pi R^2} \right)^2 r u_r \quad (0 < r < R) \quad (48)
\]
where
\( u_r \) is the radial unit vector.

\( I \) is the current.

\( r \) is the radial coordinate.

\( R \) is the radius of the arc.

\( \mu \) is the magnetic permeability.

For the radial component of the current density distribution, \( J_r \) (Equation 49), the resulting axial magnetic pressure distribution, \( P_z \), is given in Equation 50.

\[
J_r(r) = -\frac{I}{\pi R^3} \frac{dR}{dz} r \ (49)
\]

\[
P_z(r) = \frac{\mu}{2} \left( \frac{I}{\pi R^2} \right)^2 \frac{r^2}{R} \frac{dR}{dz} u_z \ (0<r<R) \ (50)
\]

where

\( u_z \) is the axial unit vector.

The total arc force is obtained by integrating \( P_r \) (Equation 48) and \( P_z \) (Equation 50); the result is Equation 51.

\[
\int_0^R (P_r(r) + P_z(r)) 2\pi r dr = \frac{\mu I^2}{8\pi} \left( 1+2\ln \frac{R_2}{R_1} \right) \ (51)
\]

where

\( R_1 \) and \( R_2 \) are the radii of the arc at the cathode and anode.
The first term in Equation 51 is the pressure induced arc force and the second term is the momentum generated force. The difficulty of clearly defining and measuring the arc expansion \((R_2/R_1)\) and measuring the pressure and momentum components individually leaves the arc model unverified.
APPENDIX B

ADJUSTMENT OF RADIOGRAPHIC EXPOSURE FACTORS

The radiographic images in this work were made by penetrating X-rays. The intensity of an X-ray beam attenuates as it penetrates a material, and thus gives information on thickness. Equation 52 expresses the relation between the incident X-ray beam intensity (I), the modulated X-ray beam intensity (I₀), the thickness (x), and the radiographic attenuation coefficient (μ) which depends on the type of material and the X-ray beam energy [15].

\[ I(x) = I_\circ \exp(-\mu x) \]  

(52)

where

I is the intensity of the modulated X-ray beam.
I₀ is the intensity of the incident X-ray beam.
μ is the linear attenuation coefficient, 1/cm.
x is the thickness, cm.

For a given material and X-ray beam energy (i.e. constant μ), the modulated X-ray intensity depends on the incident X-ray beam intensity and the material thickness. The incident intensity is determined by the X-ray tube
voltage and current. Hence for given X-ray tube parameters (i.e. constant X-ray source energy and intensity), the modulated X-ray intensity is related to the material thickness.
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