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THERMOCAPILLARITY AND ARC PHENOMENA IN
STAINLESS STEEL WELDS

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by

Stanley W. Pierce

"REVIEWED FOR CLASSIFICATION

By Thomas A. Blum (U)Date 9-13-93 "

A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science Metallurgical and Materials Engineering.

Golden, Colorado

Date _____

Signed: _____

Stanley W. Pierce
Graduate Student

Approved: _____

Dr. D.L. Olson
Thesis Advisor

Golden, Colorado

Date _____

Dr. J.J. Moore
Department Head
Metallurgical and
Materials Engineering

ABSTRACT

The goals of the present investigation were to characterize the effect of power level and power distribution on thermocapillary-induced-weld shape and to estimate the relative influence of various arc factors in determining weld shape. The characterization of thermocapillarity was done with the conduction mode electron beam welding (EBW) of low penetration and high penetration heats of type 304L stainless steel. The many arc related factors that may influence the shape of a gas tungsten arc (GTA) weld are eliminated with conduction mode EBW, and the weld shape is determined primarily by thermocapillarity. By comparing the conduction mode EB welds with GTA welds made at similar power levels the relative influences of the various arc factors were estimated.

Evidence of thermocapillarity was readily apparent in the both the conduction mode EB welds and the GTA welds. This correspondence between the processes served to demonstrate that thermocapillary convection is a dominant factor in heat-to-heat weld variation.

A one-to-one correspondence between the EBW and GTAW does not exist however. Even at relatively low power

conditions, where arc related factors are thought to be negligible, significant differences in weld shape were found between the two processes. For similar welding conditions, the EB welds displayed evidence of stronger thermocapillary convection than the GTA welds. To approximate the depth and width of the GTA welds, the EBW beam size had to be increased for the high sulfur heat, and decreased for the low sulfur heat. GTAW thermocapillary convection appears to be limited in some way and these beam size changes act to approximate this factor.

A review of the various arc related factors with respect to the observed weld shapes lead to the suggestion that a non-Gaussian arc distribution might best account for the differences between the two welding processes. This model is particularly well justified at relatively low welding current, below approximately 200 amperes. At higher current levels, from approximately 200 to 300 amperes, the arc distribution model remains consistent with the results, but the plasma shear force is also a likely contributor to weld shape development.

Additionally, there is evidence to suggest that thermocapillary flow reversal is not a factor in normal GTA welds. It was found that EBW flow reversal occurs only at high power density levels where evidence of the keyhole mode

is present. For GTA welds suspected of flow reversal however, no evidence of similar keyholing is found. Furthermore, based on the available arc size data, it appears unlikely that the GTAW process reaches power density levels comparable to those measured for the EBW flow reversal welds.

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1. INTRODUCTION

The mechanized gas tungsten arc welding (GTAW) process is used extensively for critical joining applications in industries such as aerospace, defense, and nuclear power. In exacting applications such as these, slight changes in weld fusion zone shape are often intolerable. Variations in GTA weld shape occasionally occur, even under highly controlled mechanized welding conditions.

As illustrated in Figure 1.1, the weld fusion zone shape is commonly defined in terms of the weld aspect ratio, or depth-to-width ratio (D/W), as determined from a transverse metallographic section of the weld. Also shown in this figure is a series of weld shapes which illustrate the relative difference between D/W ratios ranging from 0.1 to 10.

In many cases, weld shape variability has been linked to minor variations in impurity, or trace element, concentration from one heat of material to another. Heiple and Roper (1) proposed that thermocapillary convection (weld pool convection driven by temperature and surface tension gradients) is primarily responsible for weld shape and that trace element concentration variations drastically alter the

Figure 1.1. Weld fusion zone shape expressed in terms of depth-to-width ratio (D/W).

surface tension gradients, convective flow, and weld shape. Figure 1.2 is a typical example of heat-to-heat GTA weld shape variation. The GTA welds shown in this figure were made under identical conditions, yet the D/W ratio varied from 0.22 to 0.47 as a function of material composition. As indicated in this figure, the difference in weld shape is attributed to the different sulfur contents of the two material heats. Thermocapillary convection has been widely accepted as the primary mechanism of heat-to-heat weld pool shape variation, but it is well recognized that other convection mechanisms and arc related factors play important roles in the development of the GTA weld shape (2).

Recent computational models (3-8) have demonstrated that GTA weld shape is the product of a complicated competition between thermocapillary fluid flow and several interrelated arc phenomena. The major arc phenomena thought to influence weld shape come about as a result of the electromagnetic force in the arc and weld pool. The electromagnetic force causes weld pool convection and produces a plasma jet, which in turn causes pool deformation and shear-induced-fluid flow. The relative strength and influence of thermocapillary convection and the various electromagnetically induced factors are primarily dependent on the power level and power distribution of the arc.

(a) 10 ppm Sulfur
 $D/W = 0.22$

(b) 150 ppm Sulfur
 $D/W = 0.47$

Figure 1.2. A typical example of heat-to-heat GTA weld shape variation.

The goals of the present investigation were to characterize the effect of power level and power distribution on thermocapillarity-induced-weld shape and to estimate the relative influence of the various arc factors in determining weld shape. Characterization of power level and power density effects on thermocapillary-induced-weld shape was done with the conduction mode electron beam welding (EBW) process. The many arc related factors that may influence the shape of a GTA weld are eliminated with conduction mode EBW, and the weld shape is determined primarily by thermocapillarity. The relative influences of the various arc factors were estimated by comparison of EB and GTA welds.

2. BACKGROUND

2.1. Electron Beam Welding

Electron beam welding is a fusion welding process that uses a focused beam of high velocity electrons as the heat source. The electrons in the beam are accelerated across a high voltage at speeds approaching 70 percent of the speed of light. The beam is directed onto the workpiece and the heat for melting is produced through the impact of the high energy electrons on the surface. The majority of the electron kinetic energy is transferred to the workpiece and the energy transfer efficiency (net heat input to the workpiece divided by the net machine output energy) is approximately 90 percent (9). The power level and the size of the electron beam can be precisely controlled, independent of each other, to produce GTA-like, conduction mode welds or deep and narrow, keyhole mode welds. Figure 2.3 shows typical examples of conduction mode and keyhole mode EB welds.

2.1.1. Conduction Mode EBW.

To produce GTA-like, or conduction mode, welds with the

Figure 2.3. Typical examples of conduction mode and keyhole mode EB welds.

EBW process, the focal point of the beam is moved above, or below, the surface of workpiece by adjusting the focus coil current. In this defocused condition, the beam spot size at the workpiece surface is increased and power density is decreased. Beam focusing is discussed in more detail in section 2.1.3.

Conduction mode refers to the isotropic, or three-dimensional (3-d), transfer of heat from a relatively low power density source at the workpiece surface, into the weld and base metal. The term conduction mode may be somewhat misleading. For conduction mode EBW, as well as GTAW, heat is transferred from the heat source to the weld pool by conduction. Within the weld pool however, heat from the pool surface may not be transferred simply by conduction; convective mass transport in the liquid weld pool is often the major heat transfer mechanism.

Calculations by Tsai and Eagar (10) show that as the heat source is changed from a single point to a distributed source, pure conduction will yield semicircular to semielliptical weld shapes with D/W ratios of less than 0.5. Convection currents in the weld pool, on the other hand, redistribute the hottest metal from just under the heat source to other regions in the pool and result in D/W ratios anywhere from about 0.1 up to about 1.0. As

discussed in detail later, weld pool convection is often either radially inward, resulting in deep and narrow welds, or radially outward, resulting in shallow and wide welds. Figure 2.4 illustrates these convection currents as well as the point heat source and the distributed heat source.

The conduction mode EBW process is well suited to the study of the effects of heat source intensity and heat distribution on thermocapillary-induced-weld shape. All arc related phenomena of the GTAW process which could affect weld shape are eliminated with EBW. Unlike GTAW, where current levels over 200 amperes produce a substantial electromagnetic force (3,5,11-13), the current level for EBW is usually no more than 50 mA, and therefore electromagnetic effects are negligible. With EBW, the electrons travel in free flight and the beam size and trajectory are not influenced by weld pool variations. In contrast, in GTAW, the arc size and point of attachment to the weld pool are influenced by variations in electrical conductivity across the pool surface. Additionally, with the high vacuum version of the EBW process, shielding gas, which is another important variable in GTAW, is eliminated. Finally, and again unlike GTAW, the energy distribution of the beam is easily measured and is well described by a Gaussian function.

Figure 2.4. The relative weld shapes expected from pure conductive heat transfer (a,b) and convective heat transfer (c,d).

2.1.2. Keyhole Mode EBW.

For this investigation, the electron beam was defocused to produce conduction mode, GTA-like welds. For most commercial applications however, the key advantage of the EBW process is the unique ability to produce high aspect ratio, keyhole mode welds. At increased power density, in excess of about 500 W/mm^2 , the temperature under the beam approaches the boiling point, and increased vapor pressure over the liquid surface forms a cavity, or keyhole of depth and diameter that corresponds to the power level and diameter of the electron beam (14).

The beam power is deposited down into the material approximately uniformly along the depth of the keyhole. The heat transfer from the keyhole into the base metal is primarily perpendicular to the axis of the keyhole and thus is two-dimensional (2-d) conductive heat flow. Figure 2.5 illustrates the difference between two-dimensional and three-dimensional heat flow. The weld is formed as the keyhole progresses along the weld joint and the displaced molten metal fills in behind the keyhole and solidifies. The D/W ratio of keyhole mode EB welds is generally greater than one, and may easily exceed ten.

For a given weld depth, the keyhole mode EB process can use less total heat and generate narrower fusion and heat

Figure 2.5. Two-dimensional heat flow in keyhole mode EBW and three-dimensional heat flow in conduction mode EBW.

affected zones, resulting in more rapid solidification and smaller grain size, than a non-keyhole mode process. Keyhole mode EB welding is therefore most valuable where material properties must be minimally affected by heat and where part distortion must be minimized.

2.1.3. EBW Principles of Operation. (15)

The generation of the electron beam, and control of beam size, shape, and position, take place in the electron beam gun and column assembly. Figure 2.6 illustrates the triode gun (cathode-grid-anode), beam focusing, and beam deflection components that comprise the column assembly of the typical EB welding system. The electron beam is produced as negatively charged electrons are thermionically emitted from the surface of a resistance heated, tungsten filament cathode, and are accelerated through a central hole in a positively charged anode plate. A precisely configured bias cup surrounding the filament provides an electrostatic field that regulates the beam current flow and forms the electron cloud into a beam that may pass through the anode orifice.

Upon exiting the anode, the beam naturally tends to diverge. The divergence comes about due to mutual electrical repulsion between electrons and the small

Figure 2.6. Schematic of the electron beam welding system.

radial component of velocity that originated in the constriction of the beam at the anode. A magnetic coil is used to focus the beam to a concentrated spot on the workpiece. A current flowing through the focus coil controls the focal length, which is the distance from the gun (anode plate) to the point of minimum beam diameter (sharp focus). By adjusting the focal length, the beam diameter and energy density at the surface of the workpiece are adjusted.

For high aspect ratio, keyhole mode EB welds, which require a highly concentrated heat source, the beam is often adjusted so that the focal point is very near the surface of the workpiece. As illustrated in Figure 2.7, as the beam focal point is moved either above or below the work surface, the beam cross section at the workpiece surface is increased, and reduced aspect ratio keyhole mode welds, or conduction mode welds are produced. The conduction mode EB welds of this investigation were produced with the beam defocused above the work surface.

Just below the beam focusing coil is a set of x-y axis beam deflection coils. An oscillation generator drives the deflection coils and provides the capability of rastering the beam in various patterns such as a circle, line, or figure-eight. The amplitude, or total sweep distance, can

Figure 2.7. The relative relationship between electron beam size and focal spot position.

normally be adjusted up to about 25 mm, but it is dependent on the gun to work distance. The frequency of oscillation, and thus the surface travel speed of the beam, can be varied up to about one kHz. Like the beam focus, the beam deflection may be used to precisely manipulate the energy distribution of the beam to achieve the desired weld shape. Additionally, as described in the next section, the linear beam scanning capability is used in measuring the beam size.

All EBW guns require a vacuum level of 10^{-4} torr or lower to prevent short circuiting in the gun, loss of the beam, and possible damage to the gun components. To minimize beam scattering by gas molecules, the high vacuum type EBW system requires a vacuum level of less than 10^{-4} torr in the lower column and welding chamber. Partial vacuum and non vacuum EB systems must have a high vacuum level in the gun column, but the vacuum level is reduced or eliminated at the workpiece. The partial vacuum processes are generally used for less critical applications where increased production rates are desired, or in instances of very large assemblies where a vacuum chamber is not feasible.

2.1.4. EBW Beam Size Measurement.

Measurement of the beam size is easily accomplished with a modified Faraday cup (MFC) (14,16) apparatus such as that illustrated in Figure 2.8. A profile of the current density as a function of position of the beam is obtained by sweeping the beam in a linear path across the slit in the MFC. When electrons from the beam enter the cup, a voltage is generated across a 100 ohm, ground-path resistor. A storage oscilloscope is used to capture the voltage versus time signal. Subsequent measurement of the signal is done on the scope, or on a hard copy output from a plotter.

The beam profile is generally Gaussian in shape (14,16) and can be described by the equation:

$$j = I / (2 \pi \sigma^2) \exp(-r^2 / 2 \sigma^2) \quad [2.1]$$

where j is current density, I is total beam current, σ is the standard deviation of the distribution, and $r = (x^2 + y^2)^{1/2}$ is the distance from the center of the beam to the point, (x,y) , where j is measured. The slit in the MFC integrates the current along an axis perpendicular to the axis along which the beam is swept. The integrated current is described by the equation:

$$J = J_0 \exp(-r^2 / 2 \sigma^2) \quad [2.2]$$

Figure 2.8. Electron beam size measurement using the modified Faraday cup (MFC). (a) Beam current increment captured in MFC. (b) Resulting beam intensity distribution, full width at half maximum (FWHM) beam size, and the relationship between FWHM and σ (the standard deviation of the Gaussian curve fit).

where J_0 is the central current value (proportional to the slit width and $I / 2 \sigma^2$). As shown in Figure 2.8b, a convenient measure of beam size is the full width (time units) of the voltage pulse measured at the half-maximum amplitude (FWHM). Some investigators report EBW beam size or GTAW arc size in terms of the Gaussian standard deviation (σ). FWHM beam size measurement relates to the standard deviation of the Gaussian distribution as follows:

$$\text{FWHM} = 2.35 \sigma \quad [2.3]$$

The time unit FWHM is converted to position units through the relationship:

$$d = v t \quad [2.4]$$

where d is the FWHM distance in mm, v is sweep velocity of the beam in mm/sec, and t is the FWHM time in seconds. The sweep velocity at the center of a sinusoidal beam oscillation is given by:

$$v = \pi f A \quad [2.5]$$

where f is the oscillation frequency in Hz, and A is the total peak-to-peak oscillation amplitude in mm.

When measuring the beam size, the frequency and amplitude are adjusted through the oscillation generator.

The frequency value is verified from the data trace on the storage oscilloscope. The sweep amplitude is measured directly from a burn track that is generated as the beam is swept across an auxiliary tungsten block. The sweep velocity equation [2.5] gives the maximum velocity of the sinusoidal oscillation which occurs at the center of the sweep. The slit of the MFC must therefore be positioned at the center of the beam sweep, perpendicular to the axis of sweep.

The slit in the MFC is formed by two parallel tungsten blocks. For good resolution of the beam, the slit width is set to about one-third of the minimum expected beam FWHM. Near sharp focus, where the beam FWHM may approach a minimum of 0.080 mm, a slit width of 0.025 mm works well. As the beam size is increased, the current entering the MFC decreases. Therefore the slit width must be increased accordingly to yield a large enough signal for measurement.

Measurements of the electron beam energy distribution, by Burgardt (14), as well as those done for this work, show that the energy distribution of the beam is well described by a Gaussian function. The fact that the beam maintains a Gaussian distribution over a wide range of defocus conditions simplifies the task of understanding the effect which beam parameters may have on weld shape. There is a

problem however, because the cross sectional shape of beam may be non uniform. As mentioned previously, the slit in the MFC integrates the beam current along the slit axis, and therefore, current density information in that direction is lost and abnormalities in the beam shape may not be seen. A single scan axis will therefore not reveal precise knowledge of beam shape. A minimum of three beam scans, at rotational increments of forty-five degrees, is required to determine if the beam cross section is significantly non-circular.

Elmer et al. (17) used the MFC, incrementally rotating the slit and sweep axis, to obtain multiple beam scans which were then processed by means of computer tomography to yield a three-dimensional image of the beam current distribution. Their measurements demonstrated that the rectangular emitting surface of the ribbon type filament tends to be projected into the beam, resulting in a Gaussian power distribution of elliptical, or roughly rectangular, cross section. The rectangular cross section of the beam is often oriented approximately forty-five degrees to the x-y reference axis of the gun and work table. Figure 2.9a shows a sketch of a hypothetical EB power density contour plot similar to that reported by Elmer et al. (17). In Figure 2.9b the "footprint" of a rectangular beam is evident in the rapidly solidified termination of a high sulfur EB

Figure 2.9. Rectangular electron beam cross section evident in (a) power density contour plot (17) and (b) weld termination.

sulfur EB weld from the present study. For this weld, the weld travel direction was along the y axis and the beam foot print seen in the weld termination would presumably correspond well with the rectangular beam shape oriented diagonal to the x-y axis shown in Figure 2.9a. In the present study, beam size measurements were made with the MFC slit parallel to the y axis, and welding was performed traveling along the y axis. With this configuration, beam width properly corresponds with the transverse weld width along the x-axis.

Due to the diagonal orientation of the somewhat rectangular beam with respect to the weld travel direction, the distribution of heat (from side-to-side and front-to-back) of the weld would tend to be nonsymmetrical. This condition may account for minor asymmetry found in the cross sectional shape of some of the EB welds but is not considered to be significant with respect to the conclusions of this investigation.

For a given voltage, current, and gun-to-work distance setting, the beam size is a function of focus coil current. Figure 2.10 shows the beam size measurements for the present study. The focus current versus beam size relationship is linear over a broad range of focus settings.

Figure 2.10. Electron beam size measurements as a function of focus coil current.

2.2. Gas Tungsten Arc Welding

In the gas tungsten arc welding (GTAW) process, melting of the base metal is achieved by an arc between a non-consumable tungsten electrode and the workpiece. GTAW is a highly versatile process, which is employed in a wide range of applications and is well suited for joining the majority of fusion weldable alloys. GTAW is particularly suitable where excellent weld pool control and weld quality are required, and may be applied manually or mechanized in all positions.

The mechanized GTAW process is often chosen over manual welding to provide improved repeatability and quality. In many mechanized welding applications the GTAW process may be highly controlled, yet variations in the weld shape may sometimes be substantial. As discussed in detail later, thermocapillary convection is often the major cause of heat-to-heat variation of weld shape in type 304L stainless steel.

2.2.1. GTAW Principles of Operation. (15)

The GTAW process is illustrated in Figure 2.11. A power source provides a voltage between the electrode and the workpiece and as the inert gas becomes ionized it

Figure 2.11. Schematic of the gas tungsten arc welding process.

provides a conductive path for current flow through the arc. For the stainless steel welding to be discussed here, direct current electrode negative (DCEN), or straight polarity, is used. With DCEN, electrons emitted from the tungsten cathode flow to the workpiece and positive ions are transferred from the work to the electrode. The arc efficiency for the GTAW process is approximately 80 percent (18). This value means that 80 percent of the machine output energy is transferred into the workpiece as heat. Of the total heat flux, the electron flux accounts for approximately 90 percent of the heat transfer from the arc to the workpiece, while conduction and radiation from the high temperature plasma contribute the remainder (9).

2.2.2. GTAW Arc Size Data.

In GTAW, the energy distribution in the arc is an important variable that affects thermocapillary convection and weld shape. As discussed in detail later, the magnitude and direction of thermocapillary flow are driven by weld pool surface tension gradients which are a function of material composition and temperature gradients. The energy distribution of the arc can directly affect weld pool temperature distribution and hence influence convection and weld shape. Conversely, the weld pool may in turn affect

the energy distribution in the arc. The contour of the weld pool surface may influence the effective distribution of heat to the weld. Additionally, convection currents may affect the distribution of certain elements and compounds to which the arc is preferentially attracted and thereby modify the arc distribution.

Investigators have commonly used a split anode apparatus to measure current and heat distribution of the arc (19-22). As mentioned previously, the arc current accounts for approximately 80 percent of the heat flux to the work. Measurements show the arc current distribution to be slightly smaller than the heat distribution. For conditions of 190 amperes and an arc length of 2 mm, the data of Tsai (19) shows the arc current distribution to be 13 percent less than the arc heat distribution.

The split anode apparatus generally consists of two water cooled copper anodes separated by a small gap. The water cooling prevents melting of the anode and serves as a calorimetric fluid for measuring the heat flux to each anode. As the arc is moved from one anode, across the separation, to the other anode, the heat and current flux to each anode are recorded. From this data, heat and current density versus arc radius are determined.

Saedi and Unkel (22) developed a different, non-intrusive technique for measuring the arc. In their apparatus, a special photo diode array is used to sense the radiation intensity of the arc plasma. In measurements of both a non-melting arc on a copper anode and an actual welding arc on stainless steel, they found no difference in arc size. They also made arc measurements with the copper split anode technique and showed excellent correlation between this and the radiation techniques. Despite these results, there is considerable evidence that arc size may change as a function of material composition and weld pool convection.

Several investigators have observed a correlation between arc size and weld D/W ratio (23-28). Early investigators of variable weld penetration suspected that compositional differences in materials had the effect of modifying the arc distribution which in turn caused the weld shape to change. As mentioned previously, it is now generally accepted that material related weld shape changes come about primarily through thermocapillary convection.

It has been suggested that arc size changes, which accompany material related weld shape changes, occur as the distribution of conductivity-enhancing elements and compounds on the weld surface are affected by

thermocapillary convection (29,30). In this model, radially outward convection, which is responsible for low D/W ratio weld shapes, is thought to cause an increase in arc size as the arc-attracting-substances are moved to the pool perimeter. Likewise, a decrease in arc size may occur as arc attractors collect at the center of the high D/W ratio weld produced by radially inward convection. The effect of thermocapillary convection on the distribution of particles on the weld surface was demonstrated by Heiple and Roper (1), and also by Ball (31). The fact that the arc may be strongly attracted to oxidized base metal surfaces and oxide slag particles on the weld pool has been thoroughly documented (28,29,32,33).

The model for arc size as a function of weld pool convection is supported by the work of Savitskii and Leskov (26) who showed that calcium oxide additions to a cooled copper anode had no effect on arc size, yet additions to the weld pool on a consumable steel anode caused constriction of the arc and an increase in the weld D/W ratio. Presumably, the oxide remained in a uniform distribution on the copper anode, while on the actual weld, the oxide caused radially inward thermocapillary convection, which resulted in an increased weld D/W ratio and constriction of the arc as it was attracted to the oxide collected at the pool center. In

other work, Savitskii et al. (27) compared high D/W and low D/W ratio heats of steel for the consumable anode material, as well as argon and argon plus oxygen shielding gasses. Again as expected per this model, the arc size was smaller for the high D/W material, and as oxygen was added the arc size for both steels was decreased and the D/W ratio of both steels was increased.

Generally investigators involved in computational modeling of GTA weld shape development have assumed a Gaussian distribution for the arc current and heat flux. Measurements (19-22) have generally supported this assumption, but non-Gaussian distributions have also been reported. Nestor (21) reported many arc measurements which showed flat topped distributions and bimodal, or off-center peak, distributions. In measurements of actual welding arcs using emission spectroscopy, Mills (34) found arc conditions fluctuating from Gaussian to flat topped distributions. Additionally, as discussed in detail later, non-Gaussian distributions may occur due to the interaction between the deformed weld pool surface and the arc.

The effects of GTAW process variables, such as current, arc length, electrode preparation, and shielding gas composition, on arc size have been measured (19-22). Although the arc size values vary among these investigators,

there is a clear trend that increased current or arc length tends to cause an increase in the arc size. Because arc size naturally increases with power, the GTA process is not thought to be capable of reaching the power density levels required to form a keyhole.

For the present study, the arc size estimates used in establishing the initial EBW beam size requirements for attempting to match GTA welds was based on the work of Nestor (21) and of Tsai (19). Both Nestor and Tsai measured arc size with the split anode technique for a variety of weld current and arc length conditions. Much of the work by Nestor was done at an arc length of 6.3 mm, however, and was not directly applicable to more realistic welding arc lengths of 2 mm or less.

The work of Tsai (19) might have been applied directly to this investigation, but a discrepancy in this data lead to the questioning of the arc size magnitude values, but not necessarily the trends which were presented. It was found that Tsai favorably compared his results to those of Nestor (21), but the arc size values he presented were approximately a factor of two greater than those originally presented by Nestor. The reason for the data shift by Tsai could not be determined. Thus it was decided that arc size estimates comparable in magnitude with those of Nestor, but

extrapolated based on the trends reported by Tsai, would be used as a starting point for this investigation.

As shown in Figure 2.12, the extrapolation of arc size (arc heat distribution) based on Nestor (21) and Tsai (19) is comparable to the calculated arc size values by Choo and Szekely (4). Also shown are arc current distribution measurements by Saedi and Unkel (22), found subsequent to beginning this investigation. Given that the arc current distribution may be approximately 13 percent less than the heat distribution, the measurements of Saedi and Unkel are comparable to the measurements of Tsai.

2.3. Weld Shape Factors

As mentioned in preceding sections, weld pool convection is often responsible for dramatic alterations in weld shape. The four driving forces known to be important to GTA weld pool convection are buoyancy, electromagnetic, plasma shear, and thermocapillary. This section describes the origin of these forces and their potential influence on weld shape.

Figure 2.12. Arc heat distribution measurements as a function of GTAW power.

2.3.1. Buoyancy Convection.

Buoyancy is a driving force for weld pool circulation which is common to many welding processes. As illustrated in Figure 2.13, temperature differences within the pool result in a buoyancy convection, wherein high temperature fluid of low density rises, while low temperature fluid of high density descends. Due to the pattern of fluid rising in the pool center, then spreading radially to weld toe and descending, buoyancy flow is expected to favor an increase in weld width, and a decrease in weld depth. Of the four driving forces for GTA weld fluid flow, buoyancy is least influential (2,35-38). Because of its minor influence, and the likelihood that the buoyancy forces in the GTA and conduction EB welds are roughly equivalent, buoyancy is omitted in further considerations of weld pool development.

In GTA welding, the electromagnetic force, also known as the Lorentz force, is responsible for three main factors that contribute to the development of the weld pool shape. These factors are [1] arc force and pool depression, [2] plasma shear convection, and [3] electromagnetic convection. Figure 2.14 illustrates the electromagnetic force in the GTAW arc and weld pool. The electrical current flowing through the arc plasma and the weld pool generates a circumferential magnetic field. The interaction of the

Figure 2.13. Buoyancy induced weld pool convection.

Figure 2.14. The electromagnetic force in the arc and weld pool of the GTAW process.

current flux (J) with the magnetic field (B) produces the electromagnetic force which is directed toward the axis of the magnetic field. The Lorentz force is described by:

$$F_L = J \times B \quad 2.6$$

The constricting electromagnetic force is balanced by a radial pressure gradient in the conducting medium, acting in the opposite direction.

As the arc passes from the electrode to the pool surface, it broadens and the current density decreases. The current density in the weld pool also decreases rapidly. These divergent current distributions cause a pressure gradient along the axis of current flow, with higher pressure in the region of high current density. In the arc pressure is highest near the electrode. In the weld pool, pressure is highest at the pool surface. These pressure gradients produce the plasma jet in the arc and the electromagnetic convection in the pool. The strength of the electromagnetic force and hence the plasma jet and electromagnetic convection are primarily functions of current level.

2.3.2. GTA Arc Force and Pool Depression.

The plasma jet moves from electrode to the surface of the weld pool. As the jet impacts the weld pool, it exerts a force, referred to as the arc force, which can cause a depression in the surface of the GTA weld pool. Figure 2.15 illustrates the plasma jet and depression of the weld pool surface. Measurements on mild steel GTA welds have shown that arc force and pool depression depth are a linear function of current squared (11). The onset of pool depression was found to occur at 200 amperes. It was also found that, although the interrelationship of the arc force and pool depression is linear, the arc force alone can not account for the observed pool depression (11,39). A vortex model has been suggested to account for the discrepancy between arc force and pool depression (39).

In some cases the pool surface depression is thought to account for increased GTA weld penetration. The theory is that the depression allows for more direct heating of the base metal as the insulating layer of molten metal between the arc and bottom of the weld is decreased. This theory assumes that the arc in fact reaches the bottom of the depression. For relatively shallow depressions and where the arc length is kept short, the arc can be confined to the bottom of the depression. The arc is attracted to the

Figure 2.15. The plasma jet and weld pool depression resulting from the electromagnetic force in the GTAW process.

nearest, most conductive medium, however, and therefore for deep depressions and longer arc lengths, the arc will tend to interact with the top edges of the depression more than the bottom. In this way, the weld surface depression is thought to affect the heat flux distribution and hence weld circulation and penetration (5,39).

Choo et al. (5) calculated the effective current and heat flux profiles resulting from the interaction of a Gaussian arc and a deformed weld surface. As illustrated in Figure 2.16, the arc current may be primarily transferred to the humped edges of the pool. The roughly Gaussian current distribution of the arc may effectively become a bimodal flux to the pool. A bimodal heat flux was also predicted, but it tended to be more uniform than the current flux due to added heat conduction from the plasma jet at the pool center. As explained to a further degree in the section on thermocapillary convection, the bimodal or uniform heat distribution is expected to reduce the pool temperature gradient and reduce thermocapillary flow.

2.3.3. GTAW Plasma Shear Convection.

As the plasma jet impacts the pool surface, it sweeps outward from the pool center and viscous shear acts to induce outward fluid flow in the pool. As illustrated in

(a)

(b)

Figure 2.16. A bimodal arc current flux resulting from the interaction of the GTAW arc with the weld surface depression.

Figure 2.17, the shear flow is expected to increase GTA weld width and minimize depth as it pulls high temperature fluid from under the arc and circulates it to the pool perimeter.

Several computational models have indicated that shear flow may begin to influence weld shape at an arc current of about 200 amperes. Choo and Szekely (4) concluded that shear flow could become an important factor at current levels above 200 amperes, where the free surface of the pool begins to deform. They estimated that, at a current of 300 amperes, the shear force would be of the same order of magnitude as the thermocapillary force. Kim and Na (6) also concluded that the shear force begins to influence GTA weld shape at about 200 amperes and becomes more dominant with increased current and pool depression.

In computational and experimental studies of 200 ampere stationary GTA welds on mild steel and type 304 stainless steel, Matsunawa and Yokoya (12) concluded that shear flow is a function of arc length. They found that shear flow is negligible for a 2 mm length because the shear stress, although of great magnitude, is confined just beneath the cathode. In the case of an 8 mm arc length however (c,d), the shear stress is widely distributed over the entire pool surface and shear flow is the dominant factor determining the weld shape. The weld shape predicted as a result of

Figure 2.17. Plasma shear convection in the GTAW process.

shear flow was relatively wide and shallow, with the periphery being slightly deeper than the center.

The experimental results of Matsunawa and Yokoya (12), represented in Figure 2.18, show the deep center and shallow periphery weld for the low sulfur heat (a), and the uniformly deep weld for the high sulfur heat (b); both welded with a 2 mm arc length. Matsunawa and Yokoya suggest that the weld shapes produced by the short arc length process arise from the combined effects of thermocapillary and electromagnetic convection. At the 8 mm arc length however, the welds in both material heats have equivalent shallow center and deep periphery shapes as predicted (Figure 2.18c & d). These results suggest that as arc length is increased, the influence of shear flow increases, while that of the thermocapillary and electromagnetic forces decreases.

2.3.4. GTAW Electromagnetic Convection.

Similar to the generation of the plasma jet in the arc, the electromagnetic force causes fluid flow in the GTA weld pool. As shown in Figure 2.19, electromagnetic convection circulates radially inward and downward, transferring the central, high temperature fluid to the bottom of the weld pool, thereby acting to increase weld depth while minimizing

Figure 2.18. The effect of GTAW arc length on plasma shear induced weld shape in both low and high sulfur steel heats (12).

Figure 2.19. Electromagnetic convection in the GTAW process.

width. The combination of strong electromagnetic convection and thermocapillary flow are suspected as the cause of the deep center, shallow periphery weld shape (13) such as that shown previously in Figure 2.18a.

In computational models (7,13,35-37), it has generally been found that electromagnetic convection ranks second behind thermocapillary convection as a driving force for GTA weld shape development. Kou and Wang (36) calculated maximum flow velocities on the order of 10^3 , 10^2 , and 10 mm/s for the respective thermocapillary, electromagnetic, and buoyancy convection driving forces. Minor effects on weld shape were predicted at current levels as low as 100 amperes (13,36), and substantial electromagnetic effects are not expected at less than 200 amperes (13).

Oreper and Szekely (37) predicted increased electromagnetic convection with a decrease in arc distribution parameter (σ of Gaussian distribution). Tsai and Kou (7) predicted that the flow pattern of electromagnetic convection would tend to produce a raised center and depressed edge on the surface of the pool. A deep center and shallow periphery weld shape sometimes seen in low sulfur GTA welds has been attributed to the respective combined influences of electromagnetic and thermocapillary convection patterns (40,41).

2.3.5. Thermocapillary Convection.

Both experimental (1,42-46) and computational (7,13,35-37) studies have demonstrated that thermocapillary fluid flow is often the dominant mechanism affecting weld shape in most normal GTA welds. Thermocapillary fluid flow arises due to temperature and surface tension (γ) gradients across the surface of a weld pool. This surface tension driven fluid flow is also known as Marangoni fluid flow. Late in the 19th Century, Marangoni demonstrated that if a surface tension gradient exists on the surface of a liquid, then fluid will be drawn along the surface from regions of low surface tension to regions of high surface tension.

Surface tension is a function of the bond strength between atoms on a liquid surface. Within the bulk of a liquid, each metal atom is surrounded by other metal atoms and there is effectively no net force on it. In contrast, at the surface interface between the liquid and the gaseous atmosphere, the attraction of metal atoms to one another is stronger than the attraction to the gas atoms, and there is a net inward tension force on the liquid surface. This effect is seen in soap bubbles where uniform surface tension creates a spherical shape which resists distortion by gravitational forces acting on its small mass.

The surface tension of a liquid is affected by changes in composition and temperature. Figure 2.20 shows the effect of sulfur on the surface tension temperature dependence of type 304L stainless steel (47). The presence of surface active elements such as sulfur, oxygen, selenium, and tellurium can drastically lower the surface tension of an alloy at the melting temperature. For relatively pure metals, surface tension decreases as temperature is raised above the melting point, and the change in surface tension with temperature is negative ($-dy/dT$).

For alloys with sufficient quantities of surface active elements, and under conditions where these elements are in an uncombined state, surface tension increases with temperature ($+dy/dT$). The critical composition level at which dy/dT changes from negative to positive ($dy/dT = 0$) was estimated by Mills and Keene (47) to be about 70 ppm sulfur.

At temperatures near the melting point of the steel, surface active elements preferentially segregate to the pool surface, cause the bonds between surface atoms to be weakened, and thereby result in greatly reduced surface tension. As temperature is increased above the melting point, the concentration of surface active elements at the surface is reduced, and surface tension is increased

Figure 2.20. The effect of temperature and sulfur content on the surface tension of type 304L stainless steel (47).

($+d\gamma/dT$). This positive surface tension temperature dependence exists up to a critical temperature at which the surface active elements are no longer influential ($d\gamma/dT = 0$). Beyond the critical temperature, the alloy is expected to act similar to the pure material with $-d\gamma/dT$. The critical temperature is a function of the concentration of surface active elements in the alloy. The dependence of the critical temperature on composition for Fe-S and Fe-O systems was calculated by Sahoo et al. (48) and is shown in Figure 2.21.

A difference in temperature and hence, surface tension, between one region and another can result in the movement of fluid from the low surface tension area to the high surface tension area, and can dramatically alter GTA weld shape. Figure 2.22 illustrates the idealized thermocapillary convection and weld shape as a function of composition and peak temperature. For the $-d\gamma/dT$ alloy (Figure 2.22a), surface tension at the pool edge will be higher than at the center, and a radially outward fluid flow from the center will be generated. The outward thermocapillary flow promotes formation of a wide, shallow weld.

For the composition and temperature conditions where $d\gamma/dT$ is positive (Figure 2.22b), higher surface tension at the pool center creates a radially inward flow which

Figure 2.21. The dependence of the critical temperature (T_c @ $d\gamma/dT = 0$) on sulfur and oxygen content for Fe-S and Fe-O systems (48).

Figure 2.22. Thermocapillary convection patterns and weld shapes resulting from surface tension temperature and chemistry dependence.

converges downward similar to the electromagnetic flow, transferring the hottest metal to the bottom of the pool, thereby producing a deep and narrow weld.

In general, regardless of the welding process, increases in power and power density lead to increased peak temperatures, larger temperature gradients, and enhancement of the given thermocapillary flow and weld shape (41). However, as illustrated in Figure 2.22c, the alloy high in surface active elements may undergo a "flow reversal" as the critical temperature (T_c @ $dy/dT = 0$) is exceeded and $+dy/dT$ goes to $-dy/dT$ (3-5,42,48-50). As the difference between the critical temperature (T_c) and the peak weld temperature increases, the driving force for flow reversal increases. As shown in Figure 2.22c, when the critical temperature (T_c) is exceeded by a substantial amount, both a central, radially outward flow and a peripheral, radially inward flow are expected. This complex flow reversal pattern is expected to result in reduced weld d/w ratio as compared to the simple radially inward convection achieved at a lower peak temperature.

Burgardt and Heiple (42) have suggested that flow reversal may account for the reduction in the D/W of their sulfur and selenium doped type 304 stainless steel GTA welds as current was increased beyond about 200 amperes. Based on

an extrapolation of the measurements of Mills et al. (47), Burgardt and Heiple (42) estimated the critical temperature for flow reversal to be about 2050 degrees Celsius.

Kraus (41) measured GTA weld pool surface temperatures and presented an example of thermocapillary flow reversal occurring with a peak pool temperature of 2553 degrees Celsius. It is interesting to note however, that a different heat of the same AISI type 8630 steel alloy, which had a higher peak temperature (2708 degrees Celsius) did not exhibit indications of flow reversal. As shown earlier, in Figure 2.19 by Sahoo et al. (48), compositional differences may account for differences in the critical, flow reversal temperature.

Given that the maximum sulfur content of type 8603 steel is normally limited to 400 ppm (51), it can be seen from Figure 2.19, that the flow reversal temperature is expected to be approximately 2000 degrees Celsius. This flow reversal temperature is sufficiently low in relation to the measured peak weld temperatures that flow reversal might be expected for both of the welds reported by Kraus. This finding may cast some doubt on the assumption that flow reversal had occurred, but it could also be explained by noting the vast number of unknown factors associated with the detailed composition of the alloy and the relationship

of the flow reversal temperature to this complex alloy system.

As mentioned earlier, increased GTAW current beyond about 300 amperes may lead to a bimodal heat flux as a result of the interaction of the arc with a depressed weld pool. A computational model by Choo et al. (5) illustrated how the bimodal source is expected to affect thermocapillary convection and weld shape. Depending on the specific temperature gradient induced by the source and the surface tension coefficient of the material, the convection patterns and weld shapes could be quite complex.

Russo et al. (52) have presented experimental and computational evidence of $-dy/dT$ thermocapillary flow and weld shape modified by a bimodal laser source. In this instance, dual outward flow circuits, corresponding to the bimodal laser source, converged and turned downward at the weld center, resulting in a deeper than normal laser weld.

Pierce et al. (53) confirmed the findings of Russo et al. (52) and further characterized the sensitivity of thermocapillary flow and weld shape to bimodal heat distributions of varying intensity. An annular EB source, at varying focus conditions, was used in making conduction mode spot welds on both low and high sulfur heats of stainless steel. Figure 2.23 shows examples of the unique

Figure 2.23. Examples of weld shapes and thermocapillary convection patterns produced with a bimodal EBW heat source.

weld shapes and corresponding convection patterns produced with the bimodal heat source.

Thus far, it has been shown that weld pool temperature distribution and the presence, or absence, of surface active elements can profoundly affect thermocapillary convection and weld shape. Additionally, it has been found that non surface active elements also contribute to heat-to-heat weld variations. Aluminum, cerium, and calcium have been found to lower weld D/W (1,31,45,54,55). Mills et al. (2) showed that these are scavenger type elements that tend to react with surface active elements, such as sulfur and oxygen, forming non-surface active compounds.

As pointed out by Burgardt and Campbell (29), the bulk material composition for surface active elements is not an adequate predictor of GTA weld behavior, since unknown portions of this quantity may be tied up in stable compounds. Their data, shown in Figure 2.24, summarizes the weld D/W ratio, determined in a standardized GTAW test procedure, as a function of sulfur content for 200 heats of type 304L stainless steel. There is a clear trend of increased D/W ratio with increasing sulfur content but the scatter in the data, presumably a result of varying amounts of scavenger elements and surface active elements other than sulfur, is substantial.

Figure 2.24. Weld D/W ratio as a function of sulfur content as determined by standardized GTAW test (29).

2.4. Previous EBW Thermocapillarity Results

Previous investigators have utilized the EB process to demonstrate the influence of thermocapillary convection on GTA weld shape. Watson (56) compared GTA and conduction mode EB welds on Inconel 625 doped with aluminum, silicon, phosphorus, and sulfur. GTA and conduction mode EB welds in Inconel 625 which had not been doped both had D/W ratios of about 0.2, while the sulfur doped welds had D/W of 0.3 and 0.6 for GTAW and EBW respectively. This observation clearly demonstrated that sulfur affects GTA weld shape primarily through thermocapillarity, not through an arc related mechanism. Aluminum additions on the other hand, caused a decrease in GTAW D/W, but no change in EBW D/W. Watson (56) speculated that the influence of aluminum on GTA weld shape may occur through an arc related mechanism.

Robinson et al. (57,58) also compared GTA and EB welds. Stainless steel heats with 60 and 100 ppm sulfur yielded welds with D/W ratios of 0.2 and 0.6, respectively, for the GTA process, and 0.9 and 1.0, respectively, for the EB process. Robinson et al. (57) initially noted a similarity between the GTA and EB results and concluded that a weld pool related mechanism, and not an arc mechanism, was responsible for the variable GTA weld shape. In a later

review however, Robinson et al. (58) provided weld cross section macro photographs which showed the EB welds to be primarily keyhole mode welds. It was concluded that the keyhole mode EB welds did not effectively represent the conduction mode conditions of the welding process.

Heiple et al. (44) used the laser welding process (LW) in addition to EBW and GTAW (46) to evaluate the possible role of arc effects in heat-to-heat weld penetration variation. For the non-arc processes, both keyhole mode EB welds and non-keyhole, conduction mode EB and laser welds were made. For the GTAW process, an increase in selenium from 0 to 55 ppm yielded a change in weld D/W ratio from 0.3 to 0.8 respectively. For the keyhole EB process selenium additions had no effect on the weld D/W ratio. It was concluded that thermocapillary convection is not a factor in the weld shape development of keyhole mode welds.

For the LW process, defocused above the work, the change in weld D/W ratio as a function of selenium was similar to that of the GTA process. The laser weld D/W ratio changed from 0.3 to 1.0 as selenium was varied from 0 to 70 ppm respectively. Because the laser welding process is free of any electromagnetic, or arc phenomena that might influence weld shape development, the similar behavior of the GTA and laser welds in response to changes in selenium

clearly showed that thermocapillarity was the major mechanism responsible for the change in GTA weld shape.

The other non-arc weld trials by Heiple et al. (44,46), LW defocused below the work and defocused EBW, did not behave like the GTA welds, and did not effectively demonstrate the major role of thermocapillarity in weld shape development. For LW defocused below the work, and for defocused EBW, both the selenium doped and undoped heats had relatively high, and approximately equal D/W ratios; 0.7 for the laser welds, and 0.9 for the EB welds. From this D/W ratio data, and a review of the weld cross section macro photographs, it is seen that these were primarily keyhole mode welds, not conduction mode welds. Apparently the laser and electron beams were not sufficiently defocused to avoid formation of a keyhole.

In more recent work, Heiple et al. (59) reported on a series of EB welds made at varied focus conditions on stainless steel heats with 20 and 120 ppm sulfur. At moderate power density levels, the differences in D/W between the two material heats closely paralleled their GTAW results. As power density was increased and the keyhole mode was achieved however, weld shape was equal for both material heats, and was clearly not a function of thermocapillary convection.

Other data by Burgardt (14) also shows low and high sulfur EB weld D/W ratios converging to equality as power density is increased and the keyhole mode is achieved. In addition, however, it is clearly seen that as the D/W of the low sulfur heat increases with the onset of the keyhole mode, the D/W of the high sulfur heat rapidly declines to meet the low sulfur curve. It is apparent that this decline in the high sulfur weld D/W ratio is consistent with the model for thermocapillary flow reversal.

This investigation was intended to go beyond previous studies reviewed above. The conduction mode EB investigations by Heiple et al. (59) and Burgardt (14) are the most extensive to date, but they discuss little beyond the general similarity to GTA, and the conclusion that thermocapillarity is the major mechanism involved in heat-to-heat GTA weld penetration variation. It is apparent that there is more to be learned from the conduction mode EB weld results. For example, as mentioned in the previous paragraph, the data of Burgardt appear to show evidence of thermocapillary flow reversal as power density is increased. Because of the arc related factors associated with GTAW, the occurrence of flow reversal in welds can not be proven by GTAW experiments. Knowledge of thermocapillary flow

reversal in conduction mode EB welds however, might provide insight into this phenomena in GTAW.

It was the intention of this investigation to look carefully at the changes in conduction mode EB weld shape as a function of power density and base metal sulfur level to generate an experimental baseline of thermocapillary behavior. By then comparing the baseline behavior to GTA welds, the relative influence of arc related factors in determining weld shape could be estimated.

3. EXPERIMENTAL PROCEDURE

This experimental procedure section contains a description of the test material penetration characteristics, chemical compositions, coupon configuration and preparation. Additionally, the GTAW and EBW equipment, experimental matrices, and welding procedures are described. Finally, the weld evaluation procedures for metallographic preparation and weld feature measurement are discussed.

3.1. Material Selection and Preparation

The two heats of type 304L stainless steel used in this study were specifically chosen for their distinctly different GTAW penetration characteristics. The materials were selected based on their D/W ratio results from the standardized 150 ampere GTAW screening test. One heat had a relatively high D/W of 0.47, while the other heat had a much lower D/W of 0.22. Figure 3.25 shows the relative penetration differences between the two heats as determined by the screening test. The penetration characteristics of these materials are, for the most part, due to the different

Figure 3.25. Examples of typical weld shapes resulting from a standardized GTAW test of the two material heats. (150 amperes, 2 mm arc length).

levels of sulfur in the two heats. The high penetration heat had a sulfur level of 150 parts per million (ppm) by weight. The low penetration heat had a sulfur level of 10 ppm by weight. Table 1 of Appendix A is a partial list of the elements which make up the chemical composition of these two heats of type 304L stainless steel.

Weld coupons were machined to a length of 114 mm and a diameter of 62 mm. The machined surface finish was maintained at a surface roughness average (Ra) of 0.8 um or better. Cleaning prior to welding was done by hand with isopropyl alcohol and low lint paper towels. Cleanliness was maintained during handling through the use of clean white cotton gloves.

The welds were made circumferentially around the bar and each weld extended for an 80 degree increment with a 20 degree increment between welds. As shown in Figure 3.26, twelve welds were made per bar; three circumferential passes spaced along length of the bar, with four welds per pass. To avoid preheating effects from one weld to the next, the welds were made in sets of two, skipping a 90 degree increment between them, followed by cooling of the bar to room temperature between weld sets.

Figure 3.26. Weld coupon dimensions and weld placement.

3.2. Welding Equipment

3.2.1. GTAW Equipment.

To minimize weld pool contamination and arc variations from the welding atmosphere, the GTA welding was performed inside of a controlled atmosphere glove box. The glove box was filled with argon gas. A recirculating gas dryer was used to maintain the oxygen and water vapor content in the glove box below 50 ppm by volume. Argon shielding gas was also supplied through the welding torch at a flow rate of 7 liters/minute.

The GTA welding was performed with a fixed position torch at top-dead-center above the horizontally positioned, rotating weldment bar. The arc length, or distance from the tip of the tungsten to the surface of the workpiece, was set by means of a feeler gauge prior to initiating the weld. A lathe type fixture was used to rotate the workpiece and maintain an arc length variance of ± 0.08 mm.

A water cooled torch with a 2.38 mm diameter, 2 percent thoriated tungsten electrode was used. The electrode tip was prepared with a 10 degree included angle and was truncated to a 0.76 mm diameter. The electrode stickout, or distance from the electrode tip to the torch collet, was set at 25 mm. The electrode stickout beyond the end of the gas

cup was 12 mm. An alumina gas cup with a 9.5 mm diameter orifice was used.

The GTAW power supply was a Miller, solid state, direct current type, with a 350 ampere maximum output. A Merrick programmable controller provided control of the weld variables such as current and travel speed. A data acquisition system, built in-house at the Rocky Flats plant, was used to record current, voltage, and travel speed during the welds.

3.2.2. EBW Equipment.

The equipment used in this work was a 7.5 kW, high vacuum type, Leybold Heraeus EB welder. The 7.5 kW power level is the product of the 150 kV maximum accelerating voltage and the 50 mA maximum beam current. The electron gun was a model number CL-R167-R with a standard ribbon filament.

The EB weld setup was similar to that used for the GTA welds. The weldment bar was positioned horizontally and was rotated under the fixed position electron beam. The bar was positioned so that the beam impinged on top-dead-center of the bar. A Hardinge head rotational fixture was used with the weldment bar secured from one end with a collet. The run-out, or radial variance in the position of the bar, was

held to within 0.25 mm. This amount of change in gun-to-work distance is known to be insignificant with respect to changes in beam size. The distance from the inside top surface of the work chamber to the weld surface was fixed at 152 mm.

3.3. Welding Procedure

3.3.1. GTAW Parameter Matrix.

In an effort to generate GTA welds which might reveal the effects of the electromagnetic force factors in their cross sectional shape, a fairly broad range of weld current and arc gap settings were incorporated into the experimental design. A series of traveling autogenous GTA welds were made on both the high penetration and low penetration heats of material. The matrix was a full factorial statistical experimental design where the independent variables were the heat of material, the welding current, and the arc length. There were four levels of weld current; 100, 150, 200, and 300 amperes; and there were three levels of arc length; 1.0, 1.5, and 2.0 mm. Figure 3.27 shows the GTAW matrix layout. The arc voltage for each weld was recorded on a strip chart. The travel speed was held constant at 127 mm/minute for all the welds. Other factors associated with the experimental

Figure 3.27. The GTA weld experimental matrix.

setup, such as torch position, electrode stickout, and preweld specimen temperature were held constant.

3.3.2. EBW Parameter Matrix.

As shown in Figure 3.28, the EB weld portion of this study consisted of forty-eight welds for each material heat. Beam current and beam size were the independent variables. The travel speed was fixed at 127 mm/minute, as it was for the GTA welds. The EB accelerating voltage was fixed at 100 kV.

The initial intent behind the parameter selection for the EB welds was to match the power level and power distribution of each of the GTA welds. The major difficulty in designing the EB matrix was that the arc size for each GTAW current level and arc gap combination could not actually be measured, it could only be estimated from arc measurements and theoretical calculations in the literature. Likewise the EB power level required to match the GTA welds had to be estimated based on GTA and EB process efficiency data.

As discussed in the arc size background section, it was found that the arc size of the GTA welds in this study could vary from approximately 1.9 to 3.7 mm (FWHM), depending upon the power and arc gap. Therefore, for the first EB matrix

Figure 3.28. The EB weld experimental matrix.

(Figure 3.28, Matrix No.1), three levels of beam size, 1.9, 2.8, and 3.7 mm (FWHM), were utilized to correspond to the three GTA arc length conditions.

With the beam size held at the appropriate level for each GTA condition, the beam current was varied in an effort to account for efficiency differences between the GTA and EB processes. It was assumed, based on the literature review presented in the background section, that the conduction mode EB process efficiency would be equal to, or up to ten percent higher than, the GTA process efficiency. The effective input power to the workpiece from the GTA process was assumed to be equal to eighty percent of the product of amperage and voltage. For each GTA weld then, two EB welds were made, one at equal power, and one at ten percent less power.

The results of the first matrix indicated that a better match between EB and GTA shape could be achieved with smaller beam sizes for the low power welds, and larger beam sizes for the high power welds. A second EB weld iteration, composed of two matrices, was therefore utilized to explore these ranges. Each matrix utilized four levels of beam current and three levels of beam diameter. The low power welds (Figure 3.28 Matrix No.2a) were made at beam currents of 6, 8, 10, and 12 mA, and beam diameters of 0.76, 1.14,

and 1.52 mm. The high power welds (Figure 3.28 Matrix No.2b) were made at beam current levels of 29, 32, 35, and 38 mA, with beam diameters of 4.57, 5.84, and 7.11 mm.

3.4. Weld Evaluation Procedure

Cross sectional samples were cut from the mid-length area of each weld. These samples were mounted and then polished through 0.3 μ m alumina grit per standard metallographic procedures. Etching differences between the two material heats required that different etchants be used to optimize the contrast of the weld fusion zone with the base metal. The etching was accomplished with the electrolytic technique, using 10 percent oxalic acid solution for the high sulfur material, and 40 percent nitric acid solution for the low sulfur heat.

Measurements of the weld top surface width (W) and maximum depth (D) were made with an optical comparator set up in the reflectance mode. With the optical comparator, the weld image is reflected onto a large viewing screen and may be magnified up to fifty times. The sample is moved relative to reference cross hairs with a motorized x-y table and the measurements are read from a digital display.

4. RESULTS & DISCUSSION

In this section, the EB weld results are presented first, followed by the GTA weld results. The observations of EB weld shape as a function of power, beam size, and base metal sulfur content are presented and the applicability of the thermocapillary convection model to these results is discussed. Similarly, observations of GTA weld shape as a function of power, arc length, and base metal sulfur content will be discussed in terms of thermocapillarity and the various arc related phenomena. Following these results, comparisons are made of the EBW and GTAW results, and observations about the relative roles of thermocapillarity and the arc related phenomena are presented.

The remaining portion of the results and discussion section deals with the attempt to precisely match the individual GTA welds with EB welds. In this comparison of EB and GTA welds, theories about arc size and shape, and the role of arc phenomena in GTA welds are presented.

4.1. Electron Beam Welding Results

The data presented here are a limited and select sample which were chosen to best display the trends found to be demonstrated throughout the whole of the data. The complete set of EB weld depth and width measurements, depth-to-width ratios, and the respective beam current and beam size settings are listed in Table 2 of Appendix A.

One of the first observations was that some of the beam current and beam diameter combinations were not of high enough power density to produce melting, while other combinations resulted in excessive power density and produced keyholing. Figure 4.29 shows the EB experimental matrix in relation to the parameter ranges which define the onset of melting, and the onset of keyhole formation.

The delineation of the onset of keyholing was based on the appearance of the low sulfur EB welds. Due to radially outward thermocapillary convection, the low sulfur welds were wide and shallow, and therefore the onset of keyholing was clearly revealed by the appearance of a central spike of penetration as power density was increased.

The region of no melting was defined through a series of eleven welds where beam size or beam current was varied and the transition from melting to no melting was

Figure 4.29. The EB weld experimental matrix in relation to regions delineating the onset of melting and the onset of keyhole formation.

determined. Table 3 of Appendix A lists the data from the no melt determination exercise.

4.1.1. EBW D/W Ratio as a Function of Power.

For a given beam size, as power is increased, power density, peak temperature, and the temperature gradient are increased. Burgardt and Heiple (42) postulated that increased power density would lead to enhancement of the existing thermocapillary convection pattern, thus the welds of a $-dy/dT$ heat would tend toward lower D/W ratios, and the welds of a $+dy/dT$ heat would tend toward higher D/W ratios. It was also pointed out, however, that the high sulfur alloy may undergo a flow reversal as the critical temperature is exceeded and dy/dT changes from positive to negative.

The typical effect of increased power on weld shape and the weld D/W ratio is shown in Figure 4.30. Since the beam size was held constant for this set of welds, the power density increases with power. As expected with any welding process, increased power causes an increase in weld area for both the low and high sulfur heats of material.

At low power, from point A to B, the low sulfur welds were shallow and wide with a relatively constant D/W ratio of about 0.14. The low sulfur weld shapes are consistent with radially outward ($-dy/dT$) thermocapillary convection,

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Figure 4.30. EB weld D/W ratio as a function of power and sulfur content.

For this same power range, from point A to B, the D/W ratio of the high sulfur welds was much greater than the low sulfur welds, and it increased linearly with power from 0.32 to 0.70. The high sulfur weld shapes are consistent with the radially inward ($+d\gamma/dT$) thermocapillary convection, and as suggested by Burgardt and Heiple (42), the D/W ratio increases with increased power density.

Careful examination of the weld cross sections confirmed that, up to point B, these were conduction mode welds. The small central spike of penetration seen in the low sulfur weld at point B indicates the onset of the keyhole mode.

From point B to C, as the power density increases and the keyhole mode is enhanced, the depth of central penetration spike and the D/W ratio of the low sulfur welds increases. For the high sulfur welds on the other hand, the D/W ratios begin to decrease with increased power. This decrease in D/W ratio is consistent with thermocapillary flow reversal and thus suggests that the peak pool temperature has exceeded the critical value at which $d\gamma/dT = 0$.

The major finding of interest here is that both the peak D/W ratio and flow reversal conditions for the high sulfur heat correspond to the onset of keyholing which was

seen in the low sulfur welds. As discussed in detail later, this finding raises questions about thermocapillary flow reversal in the GTAW process since it is not expected to reach the power density associated with the onset of the keyhole mode.

4.1.2. EBW D/W Ratio as a Function of Beam Size.

The influence of increased power density on thermocapillary flow and weld shape is further demonstrated in Figure 4.31, where the D/W ratios of 1200 watt welds are plotted as a function of beam size. This plot clearly shows the same trend as the previous plot of D/W ratio as a function of power. As beam size is decreased from point B to A, power density is increased and we see the onset of the keyhole mode, resulting in increased D/W ratio of the low sulfur welds, and thermocapillary flow reversal with decreasing D/W ratio for the high sulfur welds. As beam size is increased from point B to C, the decreasing power density is accompanied by a sharp decrease in high sulfur weld D/W ratio and no change in the low sulfur D/W ratio. From point C to D, the D/W ratios of both heats drop rapidly to zero as the power density declines below the level needed for melting.

Figure 4.31. EB weld D/W ratio as a function of beam size and sulfur content.

The peak D/W ratio and flow reversal examples of high sulfur EB welds from Figure 4.31 are shown in more detail in Figure 4.32a and b, respectively. Comparison of these welds yields three differences which are supportive of the flow reversal model. First, as shown before, the decrease in weld D/W ratio which accompanies the reduction in beam size is indicative of thermocapillary flow reversal.

The second observation which supports the claim of flow reversal in the above EB welds is that with a decrease in the beam size, the surface roughness increased. The roughness increase is consistent with the increased turbulence associated with the complex flow pattern of the flow reversal model.

The third factor which is suggestive of flow reversal is the change in weld front shape from angular to rounded as beam size was decreased for the welds in Figure 4.32. This shape change indicates a reversal of flow direction from radially inward to radially outward as the beam size is decreased. Here it is proposed that the angular front shape of the weld pool is the direct result of conductive heat transfer from a rectangular cross section electron beam. In the case of the peak D/W ratio weld, radially inward thermocapillary flow acts to preserve this beam profile imprint. The rounded front shape seen in the other weld

Figure 4.32. Top surface and cross sectional shape change in high sulfur EB welds resulting from thermocapillary flow reversal as beam size is decreased.

appears to indicate that the beam imprint was "washed over" or obliterated by radially outward flow.

A similar examination was made of the two low sulfur welds, which were made under the same conditions as the high sulfur, peak D/W ratio and flow reversal welds. These welds, shown in Figure 4.33a and b, display three features which can be related to the high sulfur thermocapillary flow reversal model. First, as mentioned previously, there is a direct correlation between keyholing, which is evident in the deep central penetration of these welds, and the occurrence of both the maximum D/W ratio and flow reversal conditions in high sulfur welds.

The second feature which was looked at, with respect to thermocapillary flow reversal, was the surface roughness of the welds. The two low sulfur welds shown in Figure 4.33 have a similar degree of surface roughness that is less than that of the high sulfur flow reversal weld shown previously in Figure 4.31b. This finding supports the assertion that the high degree of surface roughness seen in the high sulfur weld is attributable to flow reversal and not some other effect of the reduction in beam size.

The asymmetrical shape seen in the reduced beam size, low sulfur weld is attributed to the influence of the rectangular beam on the convection pattern. It can be seen

Figure 4.33. Evidence of the keyhole mode in low sulfur EB welds that correspond to the high sulfur flow reversal welds.

that the asymmetry had little effect on the cross sectional weld shape, and the rectangular beam is not believed to be a significant factor in the high sulfur flow reversal case either.

The third feature which lends support for the flow reversal model is shape of the weld front seen on the top surface of the low sulfur welds in Figure 4.33. As expected with radially outward convection, for both the low sulfur welds, and the high sulfur flow reversal weld of Figure 4.31b, the imprint of the rectangular electron beam shape in the weld front tends to be obliterated.

4.2. GTA Welding Results

In this section the observations about GTA weld shape as a function of power, arc length, and base metal sulfur level are presented and the applicability of the thermocapillary convection and the various arc factor models is discussed. Table 4 of Appendix A lists the depth, width, and D/W ratio for all of the GTA welds.

4.2.1. GTAW D/W Ratio as a Function of Power.

As described in the background section, thermocapillary convection is often the major driving force for GTA weld shape development. The arc related factors which influence GTA weld shape, such as electromagnetic convection, plasma shear convection, and pool deformation, are not thought to be significant at currents below about 200 amperes. Like the EBW process, an increase in GTA power should enhance the given thermocapillary convection and weld shape tendency. Thermocapillary flow reversal and reduced high sulfur weld D/W is expected as power density is increased.

Figure 4.34 shows the typical results of increased power on weld D/W ratio for both high and low sulfur heats welded at a fixed arc length of 2 mm. The D/W ratio of the low sulfur welds tends to decrease slightly as power is increased. This D/W decrease is consistent with the thermocapillarity model of Burgardt and Heiple (42), but it differs from the constant D/W ratio seen in the EB welding results.

The decrease in low sulfur D/W and the shallow weld shape suggest that electromagnetic convection is not a dominant factor under these welding conditions. As discussed in the background section, if electromagnetic convection was a dominant factor, we would expect an

Figure 4.34. GTA weld D/W ratio as a function of power and sulfur content.

increase in D/W and possibly a deep center and shallow periphery weld shape. Although plasma shear is not considered to be a dominant factor in welds in this arc length and power range, the decrease in low sulfur weld D/W is consistent with the plasma shear model.

The D/W ratio of the high sulfur welds first increases to a maximum and then decreases with increased power. These results are consistent with the thermocapillarity model and the EB welding results. As with the low sulfur welds, plasma shear can be considered as a possible contributor to the decline in high sulfur D/W. Electromagnetic convection is expected to enhance the high sulfur D/W as power is increased, yet it is clearly not dominant in these welds.

4.2.2. GTAW D/W Ratio as a Function of Arc Length.

Increased arc length at constant current causes an increase in arc voltage, and hence power. The power density of the arc is thought to decrease however, because arc efficiency (η) decreases (60) and arc size increases (19) as the arc length is increased. Per the thermocapillary flow mechanism, an arc length increase should reduce the given D/W tendency, i.e., the D/W of the $-dy/dT$ alloy would increase, while the D/W of the $+dy/dT$ alloy would decrease (42). The other convection driving forces thought to be

affected by arc length are plasma shear and the electromagnetic force. Increased arc length has been shown to increase the effect of plasma shear, but only at currents in excess of about 200 amperes and arc lengths exceeding 2 mm (12). Plasma shear induced convection promotes a decrease in weld D/W ratio. Electromagnetic convection and weld D/W tend to decrease with increased arc length.

As shown in Figure 4.35, the high sulfur GTA welds experienced a dramatic decrease in D/W ratio as arc length was increased. This decrease is consistent with the results of Burgardt and Heiple (42). They point out that this drop in D/W for the high sulfur welds is consistent with the thermocapillarity model, since increased arc length leads to a broadening of the heat distribution and a reduction in the radially inward fluid flow.

The other factors favoring the decrease in high sulfur GTA weld D/W ratio are the decrease in electromagnetic convection, and the increased influence of plasma shear, as arc length is increased. Once again however, these arc related factors are generally not considered to be important at the power and arc length values of these welds.

The low sulfur welds acted contrary to expectations and showed a slight decrease in D/W ratio as arc length was increased. It should be noted that arc length was not found

Figure 4.35. GTA weld D/W ratio as a function of arc length and sulfur content.

to be a statistically significant variable in the regression analysis of the low sulfur GTAW data (Table 4 of Appendix A). The fact that the D/W ratio did not increase as expected however, appears to indicate that a combined influence of thermocapillarity and plasma shear driving forces exists. Plasma shear would act to oppose the tendency for a D/W increase, due to a reduced thermocapillary force, as arc length was increased.

In summary, the GTAW results are generally consistent with the thermocapillarity model and results of Burgardt and Heiple (42). Contrary to expectations for increased dominance of electromagnetic convection at the higher current levels, it was found not to be a dominant factor in these welds.

Increased dominance of plasma shear as a function of increased arc length appeared to be supported by the behavior of the low sulfur weld D/W. In every other instance, however, the effects of plasma shear would tend to compliment those of thermocapillary convection, thus yielding confounding and inconclusive results.

4.3. Comparison of EBW and GTAW

By comparing the EB and GTA weld results presented in the above discussion and figures, the relative influence of thermocapillarity and electromagnetic forces on GTA weld shape development were assessed. The EB weld shapes are thought to be a function of thermocapillary convection and variations in the intensity of the Gaussian EB heat source. The GTA weld shapes on the other hand, are presumably a function of several competing factors, all of which may be affected by arc power and arc energy distribution.

Comparisons of EB and GTA welds at precisely equivalent conditions are impossible because of the lack of actual arc distribution measurements for the GTA welds of this study. Figure 4.36 serves to demonstrate the degree of uncertainty relative to the available arc size data. In this figure, the arc measurements presented previously have been superimposed on the EB weld chart which delineates regions for the onset of melting and the onset of the keyhole mode. In addition to the uncertainty which is evident in the disparity between the two groups of arc size measurements, it can be seen that at certain conditions data from both groups is questionable. At low power, the large arc size group seems to be in error since it appears that melting

Figure 4.36. GTAW arc heat distribution measurements as a function of power plotted relative to regions delineating the onset of melting and the onset of keyhole formation for EBW.

will not occur at these conditions. Likewise, at high power, the small arc size data group comes into question since the onset of keyholing is expected at these conditions. The GTA welds in this investigation showed no evidence of keyhole behavior as seen in the EB welds.

It was found that the high sulfur welds of both the EB and GTA process display a decrease in D/W ratio at the high end of the power range. This decrease in high sulfur weld D/W ratio has generally been attributed to thermocapillary flow reversal. Since EB weld flow reversal occurs only with the onset of the keyhole mode, and GTAW does not appear to reach the keyhole conditions, thermocapillary flow reversal in normal GTA welds seems unlikely.

Further evidence which tends to refute the GTAW flow reversal model was found in comparing the shape of the proposed flow reversal welds for the EBW and GTAW processes. As shown previously in Figure 4.30 at point C, and in Figure 4.31 at point A, the shape of the EB flow reversal weld is quite different from the comparable low sulfur weld. For the EBW process, it is known that further increases in power density will lead to fully keyhole mode welds for both heats of material (14). For the GTAW process on the other hand, as shown previously in Figure 4.34 at point C, the proposed flow reversal weld is very similar to the comparable low

sulfur weld. This difference in behavior between EBW and GTAW is suggestive that a factor other than thermocapillary flow reversal, such as plasma shear, may account for the decrease in high sulfur weld D/W ratio.

Further evidence that GTAW plasma shear may be more influential than previously thought is seen in the comparison of low sulfur EB and GTA weld behavior as power is increased. With increasing power, the conduction mode EB weld D/W remains relatively constant. For the GTAW process however, increased power causes a decrease in weld D/W. This decrease in D/W ratio is consistent with an increased influence of plasma shear forces as GTAW power is increased.

This trend of decreased low sulfur D/W with increased power, also serves to demonstrate that electromagnetic convection is not a dominant factor under these welding conditions. If electromagnetic convection was a dominant force, an increase in the low sulfur weld D/W ratio would be expected. Likewise, the fact that increased power leads to a decrease in the high sulfur weld D/W again demonstrates that electromagnetic convection is not a dominant factor under these welding conditions.

Another important finding was that the EBW process showed a greater difference in the D/W ratios of the two material heats than did the GTA process. As shown in the

previous figures, the difference in the weld D/W ratio between the high sulfur and low sulfur heats changes as a function of welding parameters such as power, beam size, and arc length. At one given setting, the welds in the two materials might be drastically different, yet at a different set of conditions, they may be quite similar. As shown in Figure 4.37, for comparable welding conditions, the percentage difference between the D/W ratios of the high and low sulfur welds was much greater with the EBW process. The D/W percentage difference was calculated as follows:

$$\text{D/W pct. Difference} = (\text{HD/W} - \text{LD/W}) / \text{LD/W} * 100 \quad [4.7]$$

where HD/W is the D/W ratio of the high sulfur heat and LD/W is that of low sulfur heat. Tables 5 and 6 of Appendix A contain the D/W percent difference values for all of the GTA and EB welds respectively. For both processes, as power is increased, the D/W percentage difference first rises to a maximum and then falls.

The fact that the EBW process shows a greater heat-to-heat difference in weld D/W ratio than GTAW is thought to be due to the sole dependence of the EB weld shape on thermocapillary convection, as compared to GTAW where arc related forces presumably interact with thermocapillary flow. This finding suggests that the EBW

(a)

(b)

Figure 4.37. Percentage difference in the D/W ratio of the low sulfur and high sulfur welds for (a) the EBW and (b) GTAW processes.

process would provide improved sensitivity over GTAW in application as a material screening test for determining the relative weld penetration characteristics of various material heats.

4.4. Matching GTA Welds with Electron Beam

Based on the literature, it was assumed that below approximately 200 amperes the GTAW arc related factors would be relatively negligible compared to thermocapillary convection. With this assumption in mind, an attempt was made to find the EBW parameters required to best approximate the GTA welds, and thereby estimate the GTAW arc size based on the matched EBW beam size.

The procedure for finding the unique EB current and beam size values to produce a given weld depth and width required the use of separate EB depth, and width, regression models. These EBW regression models and an explanation of the numerical process used to determine the EBW match for a given GTA weld, are listed in Appendix B. Figure 4.38 illustrates the matching procedure in graphical terms. As shown in this example, the matching process was equivalent to finding the intersection point of the specific constant

Figure 4.38. Graphical method for determining the EBW beam current and beam size needed to approximate the depth and width of a given GTA weld. Contour lines for EB depth and width were determined by regression analysis.

depth and constant width lines taken from contour plots.

The EBW power and beam size conditions which were found to best approximate the depth and width of the GTAW matrix welds are shown in Figure 4.39. Also shown are the parameter ranges corresponding to the onset of melting, and the onset of keyhole formation, as determined for the EBW process. In this figure, it can be seen that the EBW conditions required to match the low sulfur GTA welds are very near to the onset of keyholing. Additionally it should be noted that, to match the corresponding GTA welds, the high sulfur EB welds required a beam size approximately two times that of the low sulfur EB welds.

This finding that a larger EBW beam size was needed to match the high sulfur GTA weld was rather surprising. It was thought, as least for low power conditions where arc effects should be minimal, that one set of EBW conditions could be found to match both high sulfur and low sulfur GTA welds made at a given set of welding conditions.

One possible explanation of the above anomaly is that the EBW beam size, which is required to match a GTA weld, is a true indication of the GTAW arc size. However, if this were true, it would be opposite of the previously proposed model for arc size changes as a function of base metal composition (29,30). The previous model suggested that

Figure 4.39. EB power and beam size conditions required to approximate the depth and width of the GTAW matrix welds.

outward thermocapillary convection of the low sulfur weld would tend to increase arc size, while inward convection of the high sulfur weld would tend to decrease arc size. Again, as described in the background section, this model is plausible and well supported by observations (23-28)

A better explanation for the EBW beam size and GTAW arc size anomaly appears to be that thermocapillary convection is somehow limited, or opposed in the normal GTAW process. Since it is not similarly limited in EB welding, changes to the beam energy distribution are required to artificially adjust EBW thermocapillary flow to similar levels. In this model, it is assumed that the low sulfur GTA welds have an increased D/W ratio, and high sulfur GTA welds have a reduced D/W ratio, relative to the expected results of pure thermocapillary convection. Three factors were considered for their possible role in limiting the thermocapillary effect in GTA welding. These factors are [1] electromagnetic convection, [2] plasma shear convection, and [3] a non-Gaussian arc energy distribution.

As pointed out previously, neither electromagnetic convection, nor plasma shear convection, are expected to be influential in GTA weld shape determination at currents below approximately 200 amperes. The difference in EBW beam size required to match GTA welds however, occurs

consistently from 100 to 300 amperes. At higher current levels, electromagnetic convection would tend to oppose thermocapillary flow in the low sulfur welds, and plasma shear would tend to oppose thermocapillary flow in the high sulfur welds, but both factors would tend to aid thermocapillary flow in welds of the opposite sulfur composition. Neither electromagnetic convection, nor plasma shear convection, can account for the apparent opposition to thermocapillary flow in both material heats.

As shown through the following series of four figures, comparison of the GTA and EB weld cross sections revealed certain features which are suggestive that the GTAW arc distribution may not be Gaussian as commonly assumed. This appears to be the most plausible explanation for the apparent reduction in thermocapillary effects seen in GTA welds. A more uniform GTAW energy distribution would tend to reduce the driving force for thermocapillary convection in both the low sulfur and high sulfur material heats.

Figure 4.40a and d show respectively, the low, and high sulfur GTA welds made with an arc length of 2 mm and a power level of approximately 800 watts (100 amperes).

Figure 4.40b shows the low sulfur EB weld predicted to be the best match for the given GTA weld. This match is not particularly good since the EB weld is relatively wide and

Figure 4.40. Examples of the 800 watt GTA welds and the EB weld approximations.

shallow, and has evidence of keyholing. The companion high sulfur EB weld, shown in Figure 4.40e, however, is even a worse match of the high sulfur GTA weld.

As previously shown in Figure 4.39, the high sulfur EB weld requires a beam size approximately twice that of the low sulfur weld. A relatively good match for the high sulfur material, which was achieved through an increase in beam size is shown in Figure 4.40f.

It should be noted, that the EB welds have rather prominent "wings" of melting on either side of the weld. These wings are thought to be a result of direct conduction melting from the low power density, outer region of the Gaussian EB power distribution. As demonstrated previously in the discussion of the rectangular beam shape, radially inward thermocapillary convection will tend to preserve the shape of the heat source in the weld surface. The low sulfur welds do not display the wings, presumably because the radially outward convection washes molten metal outward beyond the point where direct conduction melting from the source would occur.

Finally, to complete the comparisons of 800 watt welds, the low sulfur EB weld made at the increased beam size is shown in Figure 4.40c. Again as noted above, this beam size

condition, which provided a match for the high sulfur heat, does not provide a match for the low sulfur heat.

The next six weld cross sections, shown in Figure 4.41, chronicle the attempt to match the 1900 watt (150 amperes) GTA welds with the EB process. Again, as with the 800 watt welds, a precise match of low sulfur welds is difficult because the EB welds tend to be very shallow and wide. The smaller, 1.91 mm beam size provided a good match of the GTA weld depth, but the depth is centrally concentrated, producing a somewhat triangular weld shape, as compared to the more uniform shape of the GTA weld.

The match of the high sulfur, 1900 watt GTA weld was similar to the 800 watt example. As in this previous example, at the smaller beam size, the high sulfur EB weld is much deeper and narrower than the GTA weld. Again, by roughly doubling the beam size, a fairly good match of the high sulfur GTA weld was achieved. As in the previous example, the wing features are evident at the edges of the high sulfur EB welds.

The final series of GTA and matching EB welds is shown in Figure 4.42. In this example, the GTAW power was approximately 3700 watts (300 amperes) and the greatest influence of arc related factors was expected. The major difference between this high power example and the previous

Figure 4.41. Examples of the 1900 watt GTAW welds and the EB weld approximations.

Figure 4.42. Examples of the 3700 watt GTAW welds and the EBW weld approximations.

low power examples was that the difference between the high sulfur and low sulfur weld shapes for the GTAW process was greatly reduced. At the increased power level, the high sulfur GTA weld was relatively wide and shallow, much like the low sulfur GTA weld. This was noted earlier in the discussion of GTA weld D/W as a function of power, and was attributed to increased dominance of plasma shear forces with increased power.

The fact that the high sulfur GTA weld was so wide and shallow, made it impossible to match with the EBW process. As shown in Figure 4.42e and f, the increase in beam size acts to change the EB weld shape in the proper direction to achieve a match, but the weld remains relatively deep, and the wings of melting at the weld edges become greatly exaggerated. It should be noted that both the high sulfur and low sulfur, large beam size weld samples are missing portions of the upper right-hand edge. Based on the majority of the previous welds, it is assumed that these welds are roughly symmetrical, and the right-hand side is equivalent to the left-hand side.

The match of the 3700 watt low sulfur GTA weld was similar to the previous, lower power level examples. Again the lower beam size condition provided the better match, and

also as before, the EB weld has the distinctive triangular cross section.

The unique triangular shape seen in the majority of the low sulfur EB welds, and likewise the distinctive wings of the high sulfur EB welds, seem to correlate well with the Gaussian shape of the EB heat source and the expected thermocapillary convection patterns. The more uniform shape of the GTA welds on the other hand, could result from the combined influence of thermocapillarity and the various arc related factors, or it might result from a non-Gaussian GTAW arc.

Based on the thermocapillarity model, a more uniform heat source distribution would be expected to reduce the given thermocapillary tendencies and result in more uniform weld shapes as seen in these GTA welds. As noted in background discussion of GTAW arc size measurement, many investigators have found that often the arc is not Gaussian, but rather it might display a rather flat topped, or off-center-peak distribution (21,34).

Figure 4.43 show a series of hypothetical welds and heat source distributions which aid in illustrating the proposal that heat source shape may, at least in part, account for the differences between the GTA and EB welds. A uniform, or square wave type, heat source distribution is

Figure 4.43. Typical observed weld shapes and their relationship to the known Gaussian EBW beam distribution and the proposed uniform GTAW arc distribution.

shown for the two GTA welds. With respect to the thermocapillarity model, this uniform arc distribution seems to correspond well the observed weld shapes. For the EB welds on the other hand, the energy distribution is known to be Gaussian, and indeed the observed weld shapes, for both the concentrated and diffuse conditions, are easily accepted as the expected result of this type of energy distribution, acting to drive thermocapillary convection.

5. CONCLUSIONS

In summary, the conduction mode electron beam welding process has been shown to be a valuable means of evaluating the effect of power level and power distribution variations on thermocapillary-induced-weld shape development. Additionally, by comparing the welds of the conduction EBW and GTAW processes, the relative influence of thermocapillarity, and the various GTAW arc related factors, on GTA weld shape development was evaluated.

As demonstrated by other investigators, evidence of thermocapillarity in the development of EB weld shape is readily apparent. The development of GTA weld shape as a function of base metal sulfur content closely parallels that of EBW. This correspondence between the processes serves to demonstrate that thermocapillary convection is a dominant factor in heat-to-heat weld variation.

There are two major findings which shed new light on the role of thermocapillarity and arc related factors in GTA weld shape development.

1. Contrary to previous assumptions, there is evidence to suggest that thermocapillary flow reversal is not a factor in normal GTA welds.

It was found that EBW flow reversal occurs only at high power density levels where evidence of the keyhole mode is present. For GTA welds suspected of flow reversal however, no evidence of similar keyholing is found, and the D/W ratio of these welds is much lower than that of comparable EB flow reversal welds. Furthermore, based on the available arc size data, it was found unlikely that the GTAW process reaches power density levels comparable to those measured for the EBW flow reversal welds.

2. There is certainly some factor, or combination of factors, related to the GTAW welding processes, which accounts for the many weld shape differences between the GTAW and EBW processes.

These differences appear to be best accounted for by the assumption that the GTAW arc is not Gaussian, and that this significantly modifies thermocapillary convection. This model seems particularly compelling for the low current GTA conditions where the various electromagnetic effects are thought to be minimal. At higher currents also, the welding results are consistent with this model, but here, the effect of plasma shear may also become important.

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APPENDIX A: DATA TABLES

Table 1. Composition of type 304L stainless steel test materials, and depth-to-width ratios of standardized 150 ampere GTA welds.

MATERIAL CONTROL NUMBER	COMPOSITION (weight percent)										D/W RATIO
	Cr	Ni	Mn	Si	Mo	Co	N	C	P	S	
112350	18.4	10.4	1.5	0.56	0.091	0.046	0.035	0.024	0.023	0.015	0.47
115497	18.3	11.9	1.9	0.61	0.170	0.074	0.043	0.023	0.021	0.001	0.22

Table 2. EBW parameter settings and weld dimensions for low and high sulfur type 304L stainless steel heats.

EB SETTINGS		LOW SULFUR RESULTS			HIGH SULFUR RESULTS		
POWER (W)	FWHM (mm)	DEPTH (mm)	WIDTH (mm)	D/W RATIO	DEPTH (mm)	WIDTH (mm)	D/W RATIO
600	0.76	4.42	0.79	0.18	3.23	2.36	0.73
800	0.76	5.36	1.24	0.23	3.48	3.30	0.95
1000	0.76	6.30	1.83	0.29	4.11	3.56	0.86
1200	0.76	7.70	2.46	0.32	5.33	3.78	0.71
600	1.14	4.50	0.64	0.14	3.51	2.03	0.58
800	1.14	5.72	0.94	0.16	4.11	2.90	0.70
1000	1.14	6.55	1.32	0.20	4.50	3.51	0.78
1200	1.14	7.52	1.78	0.24	4.62	4.50	0.97
600	1.52	4.06	0.64	0.16	3.40	1.37	0.40
800	1.52	5.64	0.84	0.15	4.39	2.51	0.57
1000	1.52	6.78	1.02	0.15	4.93	3.18	0.64
1200	1.52	7.70	1.40	0.18	5.44	3.94	0.72
660	1.90	3.56	0.56	0.16	3.38	1.07	0.32
740	1.90	4.67	0.66	0.14	4.01	1.47	0.37
1090	1.90	7.11	0.97	0.14	5.51	2.92	0.53
1210	1.90	7.77	1.09	0.14	5.94	3.30	0.56
1630	1.90	9.42	1.75	0.19	6.58	4.60	0.70
1810	1.90	9.88	2.08	0.21	6.55	5.05	0.77
3200	1.90	14.78	4.67	0.32	10.01	7.19	0.72
3560	1.90	16.66	5.31	0.32	11.25	8.08	0.72
660	2.79	0.00	0.00	0.00	0.00	0.00	0.00
740	2.79	0.00	0.00	0.00	0.00	0.00	0.00
1090	2.79	6.35	0.86	0.14	5.41	2.01	0.37
1210	2.79	7.39	1.02	0.14	6.40	2.62	0.41
1630	2.79	9.80	1.37	0.14	7.32	3.94	0.54
1810	2.79	10.57	1.52	0.14	7.92	4.32	0.54
3200	2.79	15.09	3.02	0.20	9.86	7.34	0.74
3560	2.79	15.93	3.73	0.23	10.21	8.33	0.82

Table 2 (continued).

EB SETTINGS		LOW SULFUR RESULTS			HIGH SULFUR RESULTS		
POWER (W)	FWHM (mm)	DEPTH (mm)	WIDTH (mm)	D/W RATIO	DEPTH (mm)	WIDTH (mm)	D/W RATIO
660	3.68	0.00	0.00	0.00	0.00	0.00	0.00
740	3.68	0.00	0.00	0.00	0.00	0.00	0.00
1090	3.68	4.06	0.48	0.12	3.68	0.79	0.21
1210	3.68	5.59	0.81	0.15	5.31	1.57	0.30
1630	3.68	9.12	1.35	0.15	7.92	3.12	0.39
1810	3.68	10.16	1.52	0.15	8.33	3.53	0.42
3200	3.68	15.37	2.26	0.15	11.73	6.55	0.56
3560	3.68	16.84	2.64	0.16	12.09	7.04	0.58
2860	4.57	14.50	1.90	0.13	12.50	4.14	0.33
3170	4.57	15.75	2.24	0.14	13.46	4.75	0.35
3480	4.57	16.97	2.34	0.14	14.43	5.46	0.38
3780	4.57	18.16	2.64	0.15	15.04	6.22	0.41
2860	5.84	11.99	1.78	0.15	11.07	2.69	0.24
3170	5.84	13.72	2.18	0.16	12.85	3.20	0.25
3480	5.84	15.85	2.41	0.15	14.66	3.71	0.25
3780	5.84	17.75	2.74	0.15	16.89	4.39	0.26
2860	7.11	7.98	0.76	0.10	7.54	1.19	0.16
3170	7.11	10.49	1.47	0.14	9.45	1.78	0.19
3480	7.11	12.07	1.68	0.14	11.33	2.29	0.20
3780	7.11	14.66	2.24	0.15	13.36	3.40	0.25

Table 3. EBW parameter settings corresponding to the onset of melting.

(Base metal = type 304L stainless steel)
(Travel speed = 127 mm/min.)

EB SETTINGS	
POWER (W)	FWHM (mm)
148	0.50
402	1.52
501	1.93
653	2.51
897	3.58
1002	3.78
1166	4.55
1451	5.56
1500	6.63
1800	6.73
2000	7.62

Table 4. GTA parameter settings and weld dimensions for low and high sulfur type 304L stainless steel heats.

304L SULFUR (ppm)	MACHINE SETTINGS		VOLT (V)	POWER (W)	WELD DIMENSIONS		
	CURRENT (A)	ARC GAP (mm)			DEPTH (mm)	WIDTH (mm)	D/W RATIO
10	100	1.0	7.10	710	1.19	4.32	0.28
10	150	1.0	7.90	1185	1.45	6.96	0.21
10	200	1.0	8.90	1780	1.68	9.12	0.18
10	300	1.0	11.75	3525	2.29	14.58	0.16
10	100	1.5	7.35	735	1.04	4.19	0.25
10	150	1.5	8.15	1223	1.80	6.35	0.28
10	200	1.5	9.25	1850	1.80	9.35	0.19
10	300	1.5	12.05	3615	2.34	14.55	0.16
10	100	2.0	7.75	775	1.02	4.32	0.24
10	150	2.0	8.50	1275	1.83	6.50	0.28
10	200	2.0	9.65	1930	1.85	9.80	0.19
10	300	2.0	12.42	3726	2.36	15.14	0.16

Regression model for low sulfur GTA weld depth. ($R^2 = 0.8795$)
Depth = $0.019704 + 0.000039 * \text{Power} - 5.376142E-9 * \text{Power}^2$

Regression model for low sulfur GTA weld width. ($R^2 = 0.9959$)
Width = $0.005989 + 0.000234 * \text{Power} - 2.083406E-8$

NOTE: Regression models yield dimensions in inches.

Table 4 (continued).

304L SULFUR (ppm)	MACHINE SETTINGS		VOLT (V)	POWER (W)	WELD DIMENSIONS		
	CURRENT (A)	ARC GAP (mm)			DEPTH (mm)	WIDTH (mm)	D/W RATIO
150	100	1.0	6.70	670	2.24	3.30	0.68
150	150	1.0	7.60	1140	2.92	4.83	0.51
150	200	1.0	8.35	1670	3.38	6.15	0.55
150	300	1.0	10.65	3195	4.04	10.64	0.38
150	100	1.5	7.35	735	1.80	3.84	0.47
150	150	1.5	7.95	1193	2.72	5.21	0.52
150	200	1.5	8.85	1770	3.35	7.04	0.48
150	300	1.5	11.65	3495	3.35	11.81	0.28
150	100	2.0	7.80	780	1.52	4.09	0.37
150	150	2.0	8.40	1260	2.64	5.74	0.46
150	200	2.0	9.30	1860	3.20	7.42	0.43
150	300	2.0	12.20	3660	3.02	13.36	0.23

Regression model for high sulfur GTA weld depth. ($R^2 = 0.9635$)
Depth = $0.04358 - 0.590693 * \text{Arc Gap} + 0.000105 * \text{Power} - 1.961226E-8 * \text{Power}^2$

Regression model for high sulfur GTA weld width. ($R^2 = 0.9982$)
Width = $0.06313 + 0.000094 * \text{Power} + 0.000399 * \text{Arc Gap} * \text{Power}$

NOTE: Regression models yield dimensions in inches.

Table 5. Percentage difference between low and high sulfur GTA weld dimensions.

MACHINE SETTINGS		PERCENT DIFFERENCE LOW TO HIGH SULFUR (LS-HS)/LS*100		
CURRENT (A)	ARC GAP (mm)	DEPTH	WIDTH	D/W
100	1.0	-87	24	-145
150	1.0	-102	31	-191
200	1.0	-102	33	-199
300	1.0	-77	27	-142

100	1.5	-73	8	-89
150	1.5	-51	18	-84
200	1.5	-86	25	-147
300	1.5	-43	19	-77

100	2.0	-50	5	-58
150	2.0	-44	12	-64
200	2.0	-73	24	-128
300	2.0	-28	12	-45

Table 6. Percentage difference between low and high sulfur EB weld dimensions.

EB SETTINGS		PERCENT DIFFERENCE LOW TO HIGH SULFUR (LS-HS)/LS*100		
POWER (W)	FWHM (mm)	WIDTH	DEPTH	D/W
600	0.76	27	-200	-311
800	0.76	35	-165	-309
1000	0.76	35	-94	-198
1200	0.76	31	-54	-122
600	1.14	22	-220	-310
800	1.14	28	-208	-328
1000	1.14	31	-165	-287
1200	1.14	39	-153	-311
600	1.52	16	-116	-158
800	1.52	22	-200	-285
1000	1.52	27	-212	-330
1200	1.52	29	-182	-299
660	1.90	5	-91	-101
740	1.90	14	-123	-160
1090	1.90	23	-203	-290
1210	1.90	24	-202	-295
1630	1.90	30	-162	-276
1810	1.90	34	-143	-266
3200	1.90	32	-54	-127
3560	1.90	32	-52	-125
660	2.79	0	0	0
740	2.79	0	0	0
1090	2.79	15	-132	-173
1210	2.79	13	-157	-197
1630	2.79	25	-187	-285
1810	2.79	25	-183	-278
3200	2.79	35	-143	-272
3560	2.79	36	-123	-248

Table 6 (continued).

EB SETTINGS		PERCENT DIFFERENCE LOW TO HIGH SULFUR (LS-HS)/LS*100		
POWER (W)	FWHM (mm)	WIDTH	DEPTH	D/W
660	3.68	0	0	0
740	3.68	0	0	0
1090	3.68	9	-63	-80
1210	3.68	5	-94	-104
1630	3.68	13	-132	-167
1810	3.68	18	-132	-183
3200	3.68	24	-190	-280
3560	3.68	28	-166	-271
2860	4.57	14	-117	-152
3170	4.57	15	-113	-149
3480	4.57	15	-134	-175
3780	4.57	17	-136	-185
2860	5.84	8	-51	-64
3170	5.84	6	-47	-56
3480	5.84	8	-54	-66
3780	5.84	5	-60	-68
2860	7.11	5	-57	-66
3170	7.11	10	-21	-34
3480	7.11	6	-36	-45
3780	7.11	9	-52	-67

APPENDIX B: MATCHING GTA WELDS WITH EBW

For simplicity, a graphical technique was presented within the text to describe the actual numerical technique used in matching the GTA welds with the EBW process. The matching procedure was as follows. First, given the depth of a particular GTA weld, the regression model for EB depth was solved to give the required beam size for each of the values of beam current in a list ranging from 5 to 40 mA, in increments of 0.1 mA. Then, given this list of beam current and beam size sets which would produce the desired depth, the regression model for EB weld width was solved for each set of conditions. Finally, given the width of the GTA weld in question, the unique set of EB parameters required to match both the depth and width of the GTA weld were selected from the list. Table 7 contains an example of the spreadsheet setup and formulas used in this matching technique.

Table 7. Example of numerical method to determine EBW settings to match a GTA weld.

304L SULFUR (ppm)	GTA SETTINGS		GTA WELD MEASUREMENTS		EBW PARAMETERS TO MATCH GTA WELD	
	AMPS	GAP	WIDTH	DEPTH	BEAM DIAMETER	BEAM CURRENT
150	200	0.080	0.293	0.126	0.133	16.5

(NOTE: All dimensions in inches)

HIGH SULFUR DEPTH MODEL COEFFICIENTS			6	5	4	3
HSA	HSB	HSC	HSW	HSD	HSBD	HSBC
-1.315	-0.724	-0.023	-0.004	0.126	-0.033	5.0
-1.315	-0.724	-0.021	0.002	0.126	-0.031	5.1
-1.315	-0.724	0.118	0.291	0.126	0.132	16.4
-1.315	-0.724	0.119	0.293	0.126	0.133	16.5
-1.315	-0.724	0.120	0.294	0.126	0.134	16.6
-1.315	-0.724	0.121	0.295	0.126	0.135	16.7
-1.315	-0.724	0.289	0.580	0.126	0.268	38.7
-1.315	-0.724	0.290	0.582	0.126	0.269	38.8

REGRESSION MODEL FOR EBW HIGH SULFUR DEPTH (HSD) $R^2=0.970042$

$$HSD=0.030015941+0.015345415 \cdot HSBC-0.000139022 \cdot HSBC^2$$

$$-0.724455147 \cdot HSBD-1.315317704 \cdot HSBD^2$$

REGRESSION MODEL FOR EBW HIGH SULFUR WIDTH (HSW) $R^2=0.968535$

$$HSW=0.3253410+0.00906320 \cdot HSBC-0.00026464 \cdot HSBC^2+1.18575584 \cdot HSBD$$

$$-13.51902345 \cdot HSBD^2+0.12024545 \cdot HSBC \cdot HSBD$$

PROCEDURE:

1. Model EB weld depth and width as a function of beam current and beam diameter.
2. Enter coefficients for depth model ($AX^2+BX+C=0$) in spreadsheet.
3. Enter fixed beam currents in spreadsheet (5 to 40 mA).
4. Calculate beam diameter for each depth in spreadsheet.
Quadratic formula: $BD=(-B \pm \sqrt{B^2-4AC})/2A$
5. Enter the depth of the GTA weld to match and copy down the for the entire spreadsheet.
6. Calculate EB weld width based on regression model and copy down to fill spreadsheet.
7. Search calculated EB weld width column and located width that matches the GTA weld.
8. Read across spreadsheet to find beam current and beam diameter required to match both the depth and width of the GTA weld.

REGRESSION MODEL FOR EBW LOW SULFUR DEPTH (LSD) $R^2=0.924314$
$LSD=0.015553254+0.007582255 \cdot LSBC-0.652193036 \cdot LSBD$
$+2.378716761 \cdot LSBD^2-0.021982338 \cdot LSBC \cdot LSBD$
REGRESSION MODEL FOR EBW LOW SULFUR WIDTH (LSW) $R^2=0.990950$
$LSW=0.03408652+0.2245084 \cdot LSBC-0.00036326 \cdot LSBC^2+0.36022679 \cdot LSBD$
$-12.02614095 \cdot LSBD^2+0.09863105 \cdot LSBC \cdot LSBD$

The validity of the EB model estimation was evaluated by visually comparing the sample EB welds made at these parameters to the given GTA welds. In some cases, where the EB model estimates were not good matches for the corresponding GTA welds, intuitive corrections were made to the estimates. Both the original regression model estimates and the visually corrected estimates for each of the GTA welds are listed in Table 8.

The weakness of the regression model is attributed to the fact that simple depth and width measurements may sometimes misrepresent the weld shape. This effect is true for some of the low sulfur EB welds where the depth is exaggerated due to the onset of keyholing. This misrepresentation also occurs in some of the large beam size, high sulfur EB welds where the width is exaggerated due to conduction melted wings on each side of the major weld bulk.

Table 8. Regression and visual estimates of EB power and beam size values required to match the dimensions of the given GTA welds.

304L SULFUR (ppm)	GTA SETTINGS		MODEL ESTIMATE FOR MATCHING EB PARAMETERS			VISUAL ESTIMATE FOR MATCHING EB PARAMETERS		
	POWER (W)	ARC GAP (mm)	POWER (W)	FWHM (mm)	% DIFF. GTA POWER	POWER (W)	FWHM (mm)	% DIFF. GTA POWER
10	710	1.0	600	0.5	15.5	700	0.5	1.4
10	1185	1.0	1070	1.3	9.7	1100	1.1	7.2
10	1780	1.0	1000	2.0	15.7	1600	1.9	10.1
10	3525	1.0	2800	3.9	20.6	3200	3.0	9.2
10	735	1.5	570	0.6	22.4	650	0.6	11.6
10	1223	1.5	1010	0.7	17.4	1000	0.8	18.2
10	1850	1.5	1550	2.0	16.2	1700	1.9	8.1
10	3615	1.5	2780	3.7	23.1	3200	3.1	11.5
10	775	2.0	590	0.7	23.9	600	0.6	22.6
10	1275	2.0	1040	0.7	18.4	1000	0.8	21.6
10	1930	2.0	1640	2.1	15.0	1800	1.9	6.7
10	3726	2.0	2950	4.0	20.8	3300	3.1	11.4
150	670	1.0	600	1.0	10.4	600	1.0	10.4
150	1140	1.0	970	1.6	14.9	950	1.6	16.7
150	1670	1.0	1300	2.2	22.2	1300	2.2	22.2
150	3195	1.0	2550	4.5	20.2	2900	4.6	9.2
150	735	1.5	650	1.7	11.6	650	1.3	11.6
150	1193	1.5	1030	2.0	13.6	1030	2.0	13.6
150	1770	1.5	1520	2.9	14.1	1520	2.9	14.1
150	3495	1.5	3060	5.9	12.4	NA	NA	NA
150	780	2.0	730	2.3	6.4	750	1.9	3.8
150	1260	2.0	1170	2.6	7.1	1170	2.6	7.1
150	1860	2.0	1650	3.4	11.3	1650	3.4	11.3
150	3660	2.0	3580	6.7	2.2	NA	NA	NA

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