MASTER

UNIVERSITY OF CALIFORNIA
DEPARTMENT OF MECHANICAL ENGINEERING
DAVIS, CALIFORNIA

TEMPERATURE DISTRIBUTIONS IN
ELECTRON BEAM WELDING CAVITIES

By

Stanley M. Shintaku

Report No. 76-10

July 15, 1976

PURCHASE ORDER NO. 6810205

SPONSORED BY THE

REPORT NO. 76-10

LAWRENCE LIVERMORE LABORATORY

JULY 15, 1976

UNIVERSITY OF CALIFORNIA

LIVERMORE, CALIFORNIA

TEMPERATURE DISTRIBUTIONS IN
ELECTRON BEAM WELDING CAVITIES

by

Stanley M. Shintaku

University of California

Davis, California 95616

Reproduction in whole or in part is permitted
for any purpose of the United States Government

FACULTY INVESTIGATOR:

W. H. Giedt, Professor of Mechanical Engineering

NOTICE
This report was prepared as an account of work
sponsored by the United States Government. Neither
the United States nor the United States Energy
Research and Development Administration, nor any of
their employees, nor any of their contractors,
subcontractors, or their employees, makes any
warranty, express or implied, or assumes any legal
liability or responsibility for the accuracy, completeness
or usefulness of any information, apparatus, product or
process disclosed, or represents that its use would not
infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

Abstract	iii
Nomenclature	v
Introduction	1
Analysis of EB Welding Cavity Surface Forces and Temperatures	8
Cavity Force Balances	8
Cavity Temperature and Pressure Distributions	14
Apparatus Description	20
Experimental Procedure	29
Interpretation of Measurements	36
Results	42
EB Welding Cavity Temperature Distributions	42
Fusion Zone Cross Sections	47
EB Welding Cavity Peak Temperatures	52
Discussion	55
EB Welding Cavity Temperature Distributions	55
EB Welding Cavity Base Temperatures	57
Conclusions	64
Suggestions for Further Study	66
References	57
Appendices	69
A. Force Balance on an EB Welding Cavity with Base	69
Radius of Curvature a_B	
B. Pyrometer Blackbody Calibration Curve	70

ABSTRACT

Surface temperatures in electron beam welding cavities in stainless steel 304 and aluminum 1100, 2024, and 6061 were measured with a narrow band infrared radiation pyrometer. A special device was designed for mounting the radiation-sensing probe next to the electron beam gun in the welding chamber. This mounting device included a mechanism for oscillating the probe so as to scan the cavity region both perpendicular and parallel to the welding direction. At the center of its movement the probe viewed almost directly down into the welding cavity. The effect of interreflections occurring in the welding cavity were accounted for by the use of an apparent spectral cavity emittance.

Typical measured cavity temperature distributions for SS-304 ranged from 1950°C at the mouth to a peak of 2350°C at the cavity base and from 1300 to 1650°C for Al-1100. First approximation predictions of the cavity surface temperatures were determined by assuming a quasi-steady-state condition. The surface temperature is then a function of the vapor pressure, which is required to balance the surface tension and the hydrostatic pressure both of which tend to collapse the cavity. Base temperatures thus predicted were about 5% and 10% higher than measured for SS-304 and Al-1100, respectively.

It was determined that EB welding cavity base surface temperatures are relatively constant with varying penetration depth because they are more strongly dependent on the curvature at the base than on the penetration depth. Average peak temperatures for SS-304, Al-1100, Al-6061, and Al-2024 were measured to be approximately 2300, 1700, 1525, and 1475°C, respectively. The peak temperatures were lower for Al-6061 and

A1-2024 than for A1-1100 because they contained a significant amount of magnesium and zinc, both of which have comparatively high vapor pressures.

NOMENCLATURE

a	cavity radius
a_c	cavity radius at surface ($y = 0$)
a_B	cavity base radius of curvature
c_2	second Planck constant ($1.4387 \times 10^4 \text{ } \mu \text{ m}^\circ\text{K}$)
e_λ	spectral emissive power per unit area
$e_{\lambda b}$	spectral emissive power per unit area of a blackbody
g	acceleration due to gravity
h	cavity penetration depth
P_v	vapor pressure
P_H	hydrostatic pressure
P_e	electron beam impact pressure
S	surface tension
T_r	radiant (brightness) temperature
T_B	cavity base temperature
T_w	cavity wall temperature
y	vertical position in cavity
ϵ_λ	spectral emittance
$\epsilon_{\lambda a}$	apparent spectral emittance
λ	wavelength
λ_e	effective wavelength
ρ	density

INTRODUCTION

Electron beam welding (EBW) is the fusion joining of materials by bombarding the interface region of the joint with a dense stream of high energy electrons (15 to 235 keV). Electrons are emitted from a cathode heated to the thermionic emission temperature [1]* and accelerated through an electric field provided by an anode and cathode as illustrated in Figure 1 [2]. The kinetic energy of the electrons is then transferred to the material being welded upon impact, causing it to melt and some to vaporize. Displacement of the molten metal by the reactive effect of the vaporizing atoms result in a cavity as shown in Figure 2 and permits penetration of the electron beam (E3) well below the surface of the work-piece. In this way, joining of materials several centimeters thick can be accomplished.

The use of electron beams for welding is a relatively recent development, but is being used for more and more commercial and research applications. A review of the current equipment available and their characteristics can be found in Reference 3. Low voltage Pierce type and high voltage telefocus EB guns are discussed. The process has a tendency to be erratic and is not adequately understood [4,5]. Therefore, current equipment and operation are based to a large extent on experiment. A significant amount of trial and error welding runs are usually necessary to determine the welding parameter settings which yield a satisfactory weld in a new type of material or joint.

One of the main advantages of EBW is the characteristically large depth-to-width ratio of the affected area of the weld. This yields a

*Bracketed numbers refer to references at the end of the report.

Figure 1. Schematic of Electron Beam Formation

CROSS-SECTION PARALLEL TO WELD

CROSS-SECTION PERPENDICULAR TO WELD

Figure 2. Electron Beam Weld Cavity

very high welding efficiency, meaning that the total energy required to produce a weld in a given thickness of material is substantially less than the energy required by conventional welding processes. As a result, the thermal stresses are smaller in EBW because the total amount of material affected by the welding process is smaller.

Figure 3 illustrates a typical longitudinal cross section of an EB weld and shows three types of problems encountered. They include excessive porosity, cold shuts, and spiking. Spiking is the tendency of the beam to penetrate suddenly to significantly greater depths resulting in a nonuniform penetration pattern. Under extreme spiking conditions the EB may suddenly penetrate completely through a joint which can be extremely detrimental in some applications. Cold shuts, sometimes considered as cracks, are regions in which the fusion material does not bond completely to the parent material.

Depth of penetration achieved is a fundamentally important but controversial aspect of EBW. The reason for this is that the maximum penetration for electrons in a metal is of the order of a few thousandths of an inch [6]. However, penetration depths on the order of inches have been achieved. The EB weld depth cannot, therefore, be caused by the direct penetration of electrons. Nor is it caused by heat conduction from the bombarded surface because this would cause the depth-to-width ratio of the affected area to be approximately unity.

A number of investigators, including Tong [3], Hells [7], Crawford [8] and Schwartz [9] have discussed EB welding cavity development as the mechanism for EBW penetration. It was postulated that the EB passes through the metal vapor in the EB welding cavity and deposits its energy at the base and wall of the cavity upon absorption. The high surface

Figure 3. Typical Longitudinal Fusion Zone Cross-Section With Various Defects [3]

temperatures generated at the base and wall of the cavity results in a high metal vapor pressure compared to the chamber pressure. The pressure force on the base and the wall of the EB welding cavity due to the metal vapor and the electron impact pressure supports the cavity against the forces tending to collapse it, which include the hydrostatic pressure and the surface tension of the molten metal lining the cavity. It has been shown that the electron impact pressure is small compared to the vapor pressure. EB welding cavity existence is substantiated by the fact that it is possible to detect a flow of electrons through the backside of a material, with an energy which is not much less than that of the incident EB [3,4,10]. This also suggests that the metal vapor in the cavity only absorbs a small portion of the beam energy.

It appears, therefore, that the pressure of the metal vapor is essentially responsible for supporting an EB welding cavity. Since there is a strong dependence of vapor pressure of some metals on the surface temperature [11,12], the surface temperature has been postulated to play a very important role in determining the character of an EB weld. Tong [3] estimated that to balance the surface tension force for aluminum, the vapor pressure had to be on the order of 25 torr and 50 torr for iron which corresponds to surface temperatures of about 1900 and 2400°C respectively. The accuracy of these values were open to question because in the determination the hydrostatic pressure of the melt tending to collapse the cavity was neglected. To balance this force would require a higher vapor pressure and therefore a higher surface temperature.

In view of this and the fact that the estimated temperatures are well above the melting temperatures of the materials, an investigation was initiated to attempt to make actual surface temperature measurements in

and around an EB welding cavity with a small target infrared (IR) radiation pyrometer.

ANALYSIS OF EB WELDING CAVITY SURFACE FORCES AND TEMPERATURES

The surface temperature in an EB welding cavity determines the magnitude of the metal vapor pressure which sustains the cavity. To investigate the temperature levels required, a force balance analysis was performed on an EB welding cavity. A quasi-steady-state condition was assumed although there are some indications that the cavity is dynamic and oscillatory in nature [3,4,10]. This assumption was valid since time average EB welding cavity vapor pressures and surface temperatures were considered.

Cavity Force Balances

The forces acting in the y-direction (vertical) on the vapor-melt interface at the base of the cavity are illustrated in Figure 4. The geometry of the interface was approximated by a hemisphere with radius a_B . The forces acting on the hemisphere in the y-direction are those due to the pressure P_v of the metal vapor in the cavity, the surface tension S acting on the edge of the hemisphere, the hydrostatic pressure P_H of the molten metal surrounding the cavity, and the EB impact pressure P_e . Since the EB impact pressure is small compared to the metal vapor pressure [6], the force of the metal vapor is the only one which facilitates penetration, whereas the others tend to drive the base interface to the surface of the specimen. Assuming that the cavity base radius a_B is small compared to the penetration depth h results in the following equation:

$$\pi a_B^2 [P_v + P_e - P_H] - 2\pi a_B S = 0 \quad (1)$$

This yields the following expression of the vapor pressure required to support a cavity with penetration h :

Figure 4. Force Balance on the Vapor-Melt Interface at the Base of the EB Weld Cavity

$$P_v = \rho gh - \frac{2S}{a_B} \quad (2)$$

This expression is also valid for the case where a complete hemisphere does not exist at the base but the radius of curvature at the base is a_B (see Appendix A).

In addition to maintaining penetration depth, the metal vapor pressure in the EB welding cavity must support the molten metal lining the cavity wall against collapse. To determine the vapor pressure required to support the wall, a force balance was performed in the x-direction (horizontal) on the semi-cylindrical vapor-melt interface with a differential height dy as illustrated in Figure 5. The analysis is similar to that of the vertical direction in which the force of the vapor pressure balances that of the hydrostatic pressure and the surface tension which tends to collapse the cavity. Assuming the cavity is cylindrical with radius $a = a_c$ leads to the following equation:

$$(P_v - P_H) 2a_c dy - 2S dy = 0 \quad (3)$$

This yields the following expression for the vapor pressure required to support the cavity wall as a function of the vertical position y in the cavity:

$$P_v = \rho gy + \frac{S}{a_c} \quad (4)$$

Substitution of vapor pressure values from Figure 6 which shows the dependence of the metal vapor pressure on the surface temperature into Equation (2) gives the relationship between the penetration depth and the EB welding cavity base surface temperature T_B . This is illustrated graphically in Figure 7 for iron and aluminum. These results were based on available values of the surface tension [13]. The value given for aluminum is characteristic of the temperature range of the

Figure 5. Force Balance on the Vapor-Melt Interface along the Wall of the EB Weld Cavity

Figure 6. Metal Vapor Pressure Curves [11]

Figure 7. Cavity Base Surface Temperature as a Function of Penetration Depth

investigation. However, the value given for iron is for a temperature slightly above melting. It is known that surface tension decreases with increasing temperature and since molten metal temperatures in a welding cavity are well above melting, applicable values of S would be lower than the one used. In view of the variation of published values, it was believed that the decrease in S would only decrease surface temperature predictions by a maximum of 2%.

For all cases shown in Figure 7, the required base surface temperature only increased by a maximum of 3% as the penetration depth increased from 0.0 to 2.5 cm. This relative insensitivity of the base surface temperature to the penetration depth is due to the fact that a large change in the vapor pressure results from a small change in the surface temperature as shown in Figure 6.

Cavity Temperature and Pressure Distributions

Pressure variations with respect to depth y in the cavity determined for cylindrical and conical geometries of a typical stainless steel EB weld cavity are shown in Figure 8a. The cavity radius at the surface of the specimen a_c , the base radius a_b , and the penetration depth h were taken to be 0.18, 0.04 and 2.0 cm respectively. These values were based on measurements of a typical fusion zone as revealed in a cross section perpendicular to a weld. Such values are considered valid since the thickness of the liquid layer at the base of the cavity is about 2 to 4% of the total penetration depth [4] and that at the wall was assumed to be of the same order.

For the cylindrical model the pressure distribution required to support the wall is given by Equation (4). Curves are shown in Figure 8a for radii $a = a_c$ and $a = a_b$. A curve showing the base vapor pressure P_v

Figure 8a. Vapor Pressure Distribution in Model Stainless Steel Electron Beam Weld Cavities

Figure 8b. Surface Temperature Distribution in Model Stainless Steel Electron Beam Weld Cavities

required to sustain a cavity of increasing depth with base radius of curvature a_B (as given by Equation (2)) is also plotted. This varies from 69 to 81 torr as the depth of penetration varies from 0.0 to 2.0 cm. Note that only 34 torr is required to support the wall near the base of the cavity with radius a_B and penetration depth $h = 2.0$ cm. This difference is caused by the factor 2 in the first term of Equation (2) which does not appear in the corresponding term of Equation (4).

Observed cavities are not usually cylindrical, but more conical in shape. Considering a cone of half angle θ leads to the following expression for the vapor pressure required to support the wall

$$P_v = \frac{S}{a \cos \theta} + \rho g y \quad (5)$$

in which a is the radius of the cavity which varies with y . Since typical values of θ are usually less than ten degrees, $\cos \theta$ can be assumed to be unity.

The pressure distribution for a purely conical stainless steel model cavity with a radius variation of $a_C(1 - y/h)$ is also shown in Figure 8a and its corresponding surface temperature distribution in Figure 8b. As y approaches the penetration depth of 2.0 cm, the vapor pressure required to support the wall as given by Equation (5) approaches infinity because of the very small cavity radius near the base. This suggests that the force required along the sides of the cavity is governed by Equation (5) from the surface of the specimen to the base where Equation (2) must be satisfied.

A more accurate EB welding cavity model would be that of a conical cavity with a spherical base. The pressure variation for such a model with the radius variation

$$a_C - [(a_C - a_B)/(h - a_B)] y \quad (6)$$

in the conical section and a base radius of a_B was also plotted in Figure 8a. As for the cylindrical model, the base pressures determined from Equations (2) and (5) yielded different values. This results in a corresponding base surface temperature difference shown in the temperature distribution plot in Figure 8b. A base surface temperature of 2450°C is required to support a penetration depth of 2.0 cm, whereas only 2360°C is required to support the wall near the base.

Since typical EB welding cavity shapes are nearly conical, they should have a pressure distribution similar to the conical model with a spherical base. The actual pressure distribution should be between those for the purely conical model and the cylindrical model with radius a_C which are considered as the limiting cases. The vapor pressure at the base must also satisfy Equation (2) and therefore have a base radius of curvature a_B . The proposed vapor pressure variation which satisfies these conditions is shown by the dashed curve in Figure 8a. It follows that of the conical-cavity-spherical-base model most of the distance to the base. Then, it departs and satisfies Equation (2) at the base. Near the base the proposed conical cavity narrows and adjusts so as to be tangent to a base region with radius of curvature a_B . This proposed variation is shown by the dashed curve in the upper graph. In the upper portion of the cavity the radius of curvature in the vertical plane is infinite (zero curvature). As y increases the radius of curvature continuously decreases to a_B at the base.

The corresponding proposed surface temperature variation is plotted in Figure 8b. The predicted surface temperature increases from 2075°C at the specimen surface ($y = 0$) to 2450°C at the base.

A similar analysis was performed for a typical aluminum EB welding cavity where the cavity radius at the surface, the base radius, and the penetration depth were taken to be 0.3, 0.05 and 1.7 cm respectively. As before, these values were based on measurements of a typical fusion zone as revealed in a cross section perpendicular to a weld. The predicted surface temperature increases from 1595°C at the specimen surface to 1875°C at the base.

APPARATUS DESCRIPTION

This experiment was performed with the electron beam welding research facility shown in Figure 9. It includes a welding chamber, an electron beam gun and power supply, and a vacuum pumping system.

The EB welder* is rated at 10 kilowatts with a maximum accelerating potential of 50 kilovolts (kV) and a maximum beam current of 200 milliamps (mA). The electron beam is formed by a triode Pierce type gun in which the beam current may be controlled by varying a negative bias potential on a control electrode (bias cup) at a constant beam potential or by varying the cathode temperature [1]. The welding chamber consists of two sections. The upper chamber houses the EB gun and the lower chamber houses the X-Y-Z positioner table and the welding specimens.

The vacuum in the chamber is provided by a 10 inch diffusion pump backed by a 40 cfm mechanical pump. The normal operating pressure range is from 5×10^{-5} torr to 1×10^{-6} torr during a welding run. The system has an ultimate pressure of approximately 5×10^{-7} torr.

The surface temperature measuring system, which is shown in Figure 10, basically consists of a small target IR radiation pyrometer.** Radiation from the emitting cavity is focused by the optics of the infrared radiation sensing probe onto the end of a fiber optic bundle. The target spot size, specified by the manufacturer to be 0.040 inch in diameter was measured by a photographic technique to be 0.044 inch in diameter. The radiation is then transmitted through the fiber optic cable into an infrared detector head (photon counter). Here the radiation is passed

* Manufactured by Brad Thompson Industries

** Vanzetti Infrared and Computing Systems Model 1262

Figure 9. Electron Beam Welding Research Facility

Figure 10. Schematic of Temperature Measuring System

through a silicon filter and to a lead sulfide detector cell where it is converted into an electrical signal. The detector has a radiation wavelength response band of approximately 1.0 to 2.5 μm . The manufacturer recommends treating instrument measurements as monochromatic at an effective wavelength $\lambda_e = 1.526 \mu\text{m}$. Variation of this effective wavelength with temperature is indicated to be negligible.

The signal from the detector is then amplified and displayed as a direct current potential by the electronic digital console. The full-scale response time is approximately 100 milliseconds. The dc output potential was recorded by a light galvanometer type oscillograph*. The radiant temperature (brightness temperature) was then determined from the calibration curve (see Appendix B). Assuming the spectral emittance of the specimen is known, the surface temperature can then be calculated.

The infrared radiation pyrometer was calibrated with blackbody cavities. The calibration curve of pyrometer amplifier output potential as a function of blackbody temperature was obtained with the calibration facilities at the Lawrence Livermore Laboratory. This involved the use of two electrically heated blackbody cavities. One operates up to a temperature of 1000°C and the other operates in a temperature range of 1100 to 3000°C. The resulting calibration curve was found to deviate from the curve supplied by the manufacturer at temperatures above 1060°C as shown in Appendix B. The accuracy of the calibration equipment was approximately $\pm 1\%$. The radiation pyrometer has a temperature resolution of $\pm 2\%$. Therefore, the accuracy of the obtained calibration curve is considered to be approximately $\pm 3\%$.

*Brush Instrument Co. model 16-2306

During welding, metal vapor from the EB welding cavity would quickly make the aperture of the radiation-sensing probe opaque. Therefore, a system was developed which moved a 0.002 inch thick teflon film across the front of the probe at an approximate rate of 1.8 cm/s to protect it from metal vapor deposition. Attenuation of the radiation by this film was found to be approximately 5% and was accounted for in the calibration of the radiation pyrometer. Additional attenuation of the radiation due to the deposition of metal vapor on the moving film was found to be negligible compared to the attenuation due to the film alone.

To obtain measurements in and around an EB welding cavity, the IR radiation-sensing probe was mounted above the EB gun assembly as shown in Figures 11 and 12. A small opening was cut in the anode plate to allow a viewing path to the welding area. The probe sighting axis was angled from the EB axis about 4 degrees. This made it possible to sight almost directly into the welding cavity as shown in Figure 11.

In order to obtain temperature distributions in and around the EB welding cavity, a mechanism for moving the probe across the cavity was designed and is shown in Figure 13. Also shown is the mechanism for moving the teflon film across the front of the probe to protect it from metal vapor and particles given off from the hot molten metal during welding. Changing the direction of the welding table by 90 degrees enabled temperature distributions, both perpendicular and parallel to the welding direction, to be obtained as shown in Figure 14. The position of the target spot was indicated by a linear displacement transducer and recorded on a second channel of the light galvanometer type oscillograph. The frequency of probe oscillation and the range of target displacement could be varied if desired.

Figure 11. Radiation Path from EB Weld Cavity to Probe

Figure 12. Probe Positioner Assembly Mounted on the
EB Gun-Focusing Coil Assembly

Figure 13. Schematic of Probe Oscillation and Protective Film

Figure 14. Probe Oscillation Directions

EXPERIMENTAL PROCEDURE

EB welding cavity temperature measurements were made on austenetic stainless steel SS-304, aluminum Al-1100 and two types of aluminum alloy Al-2024 and Al-6061. The composition and properties of these specimens are given in Table 1 [14]. The two aluminum alloys have varying amounts of magnesium and were selected because the amount of magnesium present was thought to have some effect on the character of an EB welding cavity since its vapor pressure is strongly dependent on the temperature.

Welding runs were performed at three different welding speeds which varied the energy deposition per unit weld length. The beam potential was kept constant at 31 ± 2 kV for all welding runs. The beam current was kept constant at 155 ± 5 mA for stainless steel and 135 ± 5 mA for the aluminum and aluminum alloys. The welding potential and beam current measurements were made with the meters supplied with the EB welding machine. The average welding speed was computed by dividing the distance traveled by the time elapsed. The beam was focused approximately 0.5 cm below the surface of the specimen, since better quality welds and good penetration are attained when the EB is focused slightly below the surface. [15]

Temperature profiles perpendicular and parallel to the weld were measured for each of the four specimen types at each of the three welding speeds. Typical oscillograph records of the temperature profiles are shown in Figures 15 and 16. The probe oscillation mechanism was adjusted so that the pyrometer target passed through the maximum temperature location which was assumed to be the base of the EB welding cavity. This maximum temperature location was determined by a trial and error procedure which consisted of several welding runs. The

Table 1.
Chemical Composition and Properties of Welding Specimens

MATERIAL	CHEMICAL COMPOSITION, weight percentage		MELTING RANGE, °C	DENSITY, g/cm ³
SS-304	Cr	18.0 - 20.0	1400 - 1455	7.9
	Ni	12.0 - 18.0		
	Mn	2.00 (max)		
	Si	1.00 (max)		
	C	0.08 (max)		
A1-1100	Al	99.0 (min)	643 - 657	2.71
A1-2024	Cu	3.8 - 4.9	502 - 638	2.77
	Mg	1.2 - 1.8		
	Mn	0.5 - 0.9		
	Si	0.5 (max)		
	Fe	0.5 (max)		
	Zn	0.25 (max)		
A1-6061	Mg	0.8 - 1.2	582 - 642	2.70
	Si	0.4 - 0.8		
	Fe	0.7 (max)		
	Cu	0.15 - 0.4		
	Zn	0.25 (max)

Figure 15. Oscillograph Record of a Typical EB Weld Cavity Temperature Profile Perpendicular to the Weld

Figure 16. Oscilloscope Record of a Typical EB Weld Cavity Temperature Profile Parallel to the Weld

temperature variation history at the peak temperature location was recorded for each of the four specimen types at each of the three welding speeds. Typical temperature history oscillograph records at the peak temperature location for stainless steel and aluminum-6061 are shown in Figures 17 and 18 respectively.

Figure 17. Oscillograph Record of a Typical Temperature History of a Stainless Steel 304 EB Weld Cavity Base

Figure 18. Oscilloscope Record of a Typical Temperature History of an Aluminum 6061 EB Weld Cavity Base

INTERPRETATION OF MEASUREMENTS

Once the radiant temperature T_r was determined from the pyrometer output potential, the surface temperature T of the molten metal lining the EB welding cavity can be calculated if the apparent spectral emittance $\epsilon_{\lambda a}$ (at $\lambda = 1.526 \mu\text{m}$) of the cavity is known. To evaluate this, the spectral emittance ϵ_{λ} (at $\lambda = 1.526 \mu\text{m}$) of the molten surface, the effect of internal reflections in the cavity, and possible absorption and emission by the metal vapor must be determined.

There is very little existing data on the spectral emittance of molten metals, especially at the effective wavelength of the pyrometer ($1.526 \mu\text{m}$). Spectral emittances at the standard wavelength ($0.65 \mu\text{m}$), which is near $1.526 \mu\text{m}$ for liquid iron and liquid steel, are both quoted to be 0.37 in Reference 16. Spectral emittances for solid SS-304 at 1000°C ranging from 0.2 to 0.3 in the wavelength band between 1.0 and $2.5 \mu\text{m}$ are given in Reference 12.

In the absence of directly applicable data a value for ϵ_{λ} was determined experimentally utilizing the pyrometer in the welding chamber vacuum environment. A sample of stainless steel 304 was heated by a low power EB so that a pool of liquid metal existed at the target location of the probe. The cold trap on the pumping system was filled with liquid nitrogen to minimize oil contamination of the molten surface. This was necessary to simulate the surface conditions of the virgin molten metal lining the EB welding cavity which is believed to be protected by the metal vapor existing in and continually flowing out of the cavity. Figure 19 shows a typical cooling curve which was obtained by allowing the molten pool to cool and solidify. The radiant temperature T_r corresponding to melting of the molten pool is indicated by the characteristic cooling curve plateau

Figure 19. Oscilloscope Record of a Typical
Stainless Steel Cooling Experiment

caused by the latent heat released during solidification.

An expression for the spectral emittance was derived from the following relation.

$$e_{\lambda} = \epsilon_{\lambda} e_{\lambda b} \quad (7)$$

where e_{λ} and $e_{\lambda b}$ are the spectral emissive powers per unit area of the radiation emitted from a real surface and a blackbody surface at an equivalent temperature respectively. Substitution of Planck's Radiation Law for the emissive powers yielded the following expression for the spectral emittance

$$\epsilon_{\lambda} = \frac{[e^{\frac{c_2}{\lambda T_s}} - 1]}{[e^{\frac{c_2}{\lambda T_r}} - 1]} \quad (8)$$

where c_2 is the second Planck constant and is equal to $1.4387 \text{ } \mu\text{m}^{\circ}\text{K}$.

Since 1.0 is small compared to the exponential terms for typical values of T_r and T_s , Equation (8) reduces to the following equation as recommended by the pyrometer manufacturer:

$$\epsilon_{\lambda} = \exp \left[\frac{c_2}{\lambda} \left(\frac{1}{T_s} - \frac{1}{T_r} \right) \right] \quad (9)$$

The spectral emittance was then calculated by substituting the melting temperature (mean value) from Table I for T_s , the plateau radiant temperature determined from the cooling experiment for T_r and the effective wavelength ($1.526 \text{ } \mu\text{m}$) for ϵ_{λ} . The calculated spectral emittance of the SS-304 was found to be approximately 0.39 which is in good agreement with the 0.37 value for the standard wavelength $0.65 \text{ } \mu\text{m}$ given in the literature for liquid iron and liquid steel.

Any radiation reflecting off the target area to the probe would tend to increase the calculated emittance above the actual value.

Several possibilities were investigated, including radiation emitted from the EB gun filament reflecting off the anode plate and entering the probe, and re-reflection in the focus coil housing. No effect on the emittance could be detected.

Unfortunately, the spectral emittance ($1.526\text{ }\mu\text{m}$) of the aluminum could not be determined by a similar experiment because at its melting temperature the output of the pyrometer available was not adequate to obtain an accurate measurement. However, measurements made by Schauer [17] with a similar but shorter focal length IR radiation pyrometer ($1.0\text{--}2.5\text{ }\mu\text{m}$) and using a thermocouple to determine molten metal temperatures indicated an emittance range of 0.15 to 0.25 from melting up to 1600°C . The mean value 0.2 was, therefore, used for all three aluminum specimen types. It was assumed that the spectral emittance of the two aluminum alloys are dominated by the aluminum content which constitutes at least 94% by weight.

In considering the possible effect of absorption and emission of radiation by the metal vapor in the welding cavity, it was first concluded that with only atoms present no vibration-rotation bands would exist. Cross sections for scattering are very small [18] so this mechanism can be neglected. Absorption could occur, however, by an inverse Bremsstrahlung process [19] when an electron passes near a positive ion or an atom. For the conditions existing in a welding cavity the number density of atoms was estimated to be around 10^{17} per cm^3 . From the Saha equation at the maximum temperature involved, the electron density was found to be of the order of 10^{10} per cm^3 . With these values, absorption coefficients for either of the possible Bremsstrahlung processes were negligibly small. Hence, absorption and emission of radiation by the metal vapor was neglected.

Since the geometry of the EB welding cavity facilitates a large

amount of interreflections within the cavity, a significant portion of the radiation entering the probe is reflected from the target area. Therefore, assuming all of the radiation entering the probe was emitted from a target area having a spectral emittance of the molten metal would result in an erroneously high calculated surface temperature. Instead the probe indicates the magnitude of the radiation coming from the cavity, which would include emitted and reflected radiation. When determining the surface temperature with a pyrometer, this so-called "cavity effect" can be accounted for by the use of an apparent spectral emittance $\epsilon_{\lambda a}$ in Equation (9), that is:

$$T_s = \left[\frac{\epsilon_{\lambda}}{c_2} \ln \epsilon_{\lambda a} + \frac{1}{T_r} \right]^{-1} \quad (10)$$

In doing this, all of the radiation entering the probe is treated as though it were emitted from the target area with the cavity effect being compensated for by the apparent spectral emittance. Since surface temperature variation has been shown to be modest, it is possible to estimate the cavity reflection effect from calculations for a uniform surface temperature cavity, as given in Reference 20. Although this was determined for total emittance, it is applicable for spectral emittances since a gray surface is assumed. Assuming a conical cavity with a half angle of approximately eight degrees, a diffusely reflecting surface, and a surface spectral emittance of 0.39, an apparent spectral emittance of 0.7 for stainless steel 304 was determined. A similar aluminum cavity with a surface spectral emittance of 0.2 yielded an apparent spectral emittance of 0.5. It is difficult, however, to specify the accuracy of these values because they are dependent on factors which

are not precisely known. These include possible partial specular-diffuse reflection, variations in the cavity geometry, and variations in the surface spectral emittance. Therefore, some of the results were presented for a range of apparent spectral emittances. For convenience the apparent spectral emittance $\epsilon_{\lambda a}$ will be denoted by simply ϵ_{λ} .

RESULTS

EB Welding Cavity Temperature Distributions

Typical stainless steel (SS-304) EB welding cavity temperature distributions both perpendicular and parallel to the welding direction are plotted in Figures 20 and 21 respectively. They were determined from pyrometer records using values of 0.39 and 0.7 for the apparent emittances. The latter was estimated to apply to radiation coming from a welding cavity. The curves based on $\epsilon = 0.7$ are lower by a maximum of 500°C than the curves for $\epsilon = 0.39$. These results show the temperature in the cavity increases from melting to a peak of approximately 2300°C, assuming $\epsilon = 0.7$ to be applicable. The temperature profile perpendicular to the weld is symmetrical about the peak location. The measured width of the fusion zone at the specimen surface is also indicated in Figure 20. Note that the boundaries are in general agreement with the locations where the measured temperature curve reaches the melting value (with $\epsilon = 0.39$). This would be expected since as the edge of the cavity is approached the radiation probe would actually be viewing the molten metal surrounding the cavity on the surface of the specimen ($y = 0$).

The temperature profile parallel to the weld (Figure 21) is not symmetrical about the peak temperature location. The temperature on the leading side (left side) of the profile increases at a higher rate with respect to the pyrometer target position than it decreases on the trailing side. Also, the temperatures on the trailing side are above melting at a further distance from the peak location than on the leading side.

Corresponding typical EB welding cavity temperature distributions for aluminum (Al-1100) are plotted in Figures 22 and 23. In this case results were evaluated for $\epsilon = 0.2$ and $\epsilon = 0.5$. Again the latter was

Figure 20. Typical Stainless Steel EB Welding Cavity Temperature Distribution Perpendicular to Weld

Figure 21. Typical Stainless Steel EB Welding Cavity Temperature Distribution Parallel to Weld.

Figure 22. Typical Aluminum EB Welding Cavity Temperature Distribution Perpendicular to Weld.

Figure 23. Typical Aluminum EB Welding Cavity Temperature Distribution Parallel to Weld.

estimated to apply to radiation coming from a welding cavity. The curves based on $\epsilon = 0.5$ are lower by a maximum of 450°C than those based on $\epsilon = 0.2$. With $\epsilon = 0.5$ the peak temperature is approximately 1650°C . As in the case of the stainless steel temperature profile perpendicular to the weld, the corresponding aluminum profile is symmetrical about the peak temperature location. The measured width of the fusion zone at the specimen surface is indicated in Figure 22. Again, the boundaries are in general agreement with the locations where the measured temperatures indicate melting (with $\epsilon = 0.2$). The temperature on the leading side of the profile parallel to the weld (Figure 23) increases at approximately the same rate as it decreases on the trailing side. As for the case of stainless steel, the temperatures on the trailing side are above melting at a further distance from the peak location than on the leading side.

Fusion Zone Cross Sections

Typical fusion zone cross sections both perpendicular and parallel to the weld at three welding speeds are shown for SS-304, Al-1100, Al-6061 and Al-2024 in Figures 24, 25, 26 and 27 respectively. The stainless steel cross sections reveal a relatively uniform penetration. There is no evidence of spiking or of base porosity. The perpendicular and parallel cross sections of run No. 16 (welding speed = 1.2 cm/s) indicate inconsistent results in that the perpendicular cross section shows a greater depth of penetration. The explanation for this is that the conical nature of the fusion zone requires precision grinding to reveal the plane of maximum penetration [4]. Since this maximum penetration was assumed to coincide with the plane passing through the center of the weld and sectioning was aligned by eye, deviations like the above were anticipated. This type of difference also occurs in the Al-1100 run no. 73 in Figure 25.

BEAM POTENTIAL 32 kV
BEAM CURRENT 155 mA
WELDING SPEED 0.5 cm/s

SS-304

Run No. 15

BEAM POTENTIAL 33 kV
BEAM CURRENT 150 mA
WELDING SPEED 0.8 cm/s

SS-304

Run No. 21

BEAM POTENTIAL 33 kV
BEAM CURRENT 160 mA
WELDING SPEED 1.2 cm/s

SS-304

Run No. 16

Figure 24. Typical Stainless Steel 304 Fusion Zone Cross-Sections

BEAM POTENTIAL 31 kV
BEAM CURRENT 135 mA
WELDING SPEED 0.5 cm/s

BEAM POTENTIAL 31 kV
BEAM CURRENT 140 mA
WELDING SPEED 0.8 cm/s

BEAM POTENTIAL 31 kV
BEAM CURRENT 140 mA
WELDING SPEED 1.2 cm/s

Figure 25. Typical Aluminum 1100 Fusion Zone Cross-Sections

BEAM POTENTIAL 31 kV
BEAM CURRENT 130 mA
WELDING SPEED 0.5 cm/s

BEAM POTENTIAL 31 kV
BEAM CURRENT 135 mA
WELDING SPEED 0.8 cm/s

BEAM POTENTIAL 31 kV
BEAM CURRENT 135 mA
WELDING SPEED 1.2 cm/s

Figure 26. Typical Aluminum 6061 Fusion Zone Cross-Sections

BEAM POTENTIAL 31 kV
 BEAM CURRENT 135 mA
 WELDING SPEED 0.5 cm/s

BEAM POTENTIAL 31 kV
 BEAM CURRENT 135 mA
 WELDING SPEED 0.8 cm/s

BEAM POTENTIAL 31 kV
 BEAM CURRENT 135 mA
 WELDING SPEED 1.2 cm/s

Figure 27. Typical Aluminum 2024 Fusion Zone Cross-Sections

The Al-1100 cross sections also showed no evidence of spiking or base porosity. The Al-6061 cross sections showed penetration depth variation (spiking) at the two slower welding speeds and base porosity at the lowest speed. The Al-2024 cross sections showed base porosity at all three welding speeds and some spiking at the fastest speed.

EB Welding Cavity Peak Temperatures

Average peak temperatures and average penetration depths for each of the four specimen types at each of the three welding speeds are listed in Table 2. Also included in this table are the values of the energy deposition per unit weld length and the emittance used in calculating the corresponding peak temperatures. The peak temperatures for stainless steel are approximately an average of 600°, 825° and 775°C higher than that of Al-1100, Al-2024, and Al-6061 respectively. In most cases the average penetration depth increases with increasing energy deposition per unit weld length.

Representative variations of the peak temperature during EB welding are listed in Table 3. There is significantly more variation for the two aluminum alloys than for the aluminum and stainless steel. Typical oscillograph records showing variations of the pyrometer output potential (and hence cavity temperature) for stainless steel 304 and aluminum 6061 are shown in Figures 17 and 18 respectively.

Table 2. Representative Peak Temperatures and Penetration Depths

MATERIAL	WELDING SPEED, cm/s	AVERAGE PEAK TEMPERATURE, °C	AVE. PENETRATION DEPTH, cm	ENERGY DEPOSITION 10^4 J/cm	SPECTRAL EMITTANCE
STAINLESS STEEL 304	0.5	2305	2.1	10.0	0.7
	0.8	2230	1.3	6.2	0.7
	1.2	2300	0.9	4.5	0.7
ALUMINUM 1100	0.5	1680	1.9	8.5	0.5
	0.8	1705	1.0	5.3	0.5
	1.2	1695	0.7	3.6	0.5
ALUMINUM 2024	0.5	1425	1.5	8.5	0.5
	0.8	1465	1.8	5.1	0.5
	1.2	1505	1.4	3.5	0.5
ALUMINUM 6061	0.5	1495	2.4	8.5	0.5
	0.8	1570	1.7	5.1	0.5
	1.2	1525	1.1	3.5	0.5

Table 3. Representative Peak Temperature Variations

MATERIAL	PEAK TEMPERATURE VARIATION [*] , %	MAGNITUDE OF TEMPERATURE VARIATION [*] , °C	SPECTRAL EMITTANCE
SS-304	1.4	35	0.7
ALUMINUM 7100	1.3	25	0.5
ALUMINUM 2024	5.1	30	0.5
ALUMINUM	7.5	125	0.5

* variation from mean value

DISCUSSION

EB Welding Cavity Temperature Distributions

Referring to Figures 20 and 22, the general trend of the temperature in an EB welding region is to increase from melting to a peak value. However, the predicted distribution in an EB welding cavity (see Figure 8b) varies from a temperature well above melting at the surface of the specimen ($y = 0$) to a peak temperature at the base. In the case of stainless steel 304, the measured temperature increased from about 1460°C (liquidus temperature) to a peak of 2350°C ($\epsilon_\lambda = 0.7$), whereas the predicted temperature increased from 2075 to 2450°C. The difference of about 600° in the lower temperatures can be explained by the reasonable assumption that the probe also views the molten metal surface surrounding the cavity opening as illustrated in Figure 28. As the probe target moves from the solid-liquid interface on the specimen surface to the cavity opening, the measured temperature increases from melting to 1950°C which is well above melting. This value was arrived at by assuming a proposed variation of the measured temperature distribution represented by the dashed curve in Figure 28. The surface emittance of 0.39 would apply near the solid-liquid interface at the specimen surface. As the probe target moves across the molten metal at the specimen surface and into the EB welding cavity region, the emittance increases continuously to 0.7 which would apply to radiation coming out of the cavity. Thus, the measured EB welding cavity temperature distribution actually ranged from 1950 to 2350°C. These values were lower than the predicted values by a maximum of 5%. In a similar analysis, the temperature distribution in the aluminum 1100 EB welding cavity ranged from approximately 1400°C to 1650°C, which were also lower than the predicted values by a maximum of

Figure 28. Comparison of Measured and Predicted Temperature Distributions in a Typical SS-304 EB Welding Cavity.

10%. Low temperature measurements could be a result of using emittances which are higher than applicable. The predicted temperature distributions are only approximations because the EB welding cavity dimensions used were approximations and steady state conditions were assumed. It still can be concluded that a temperature distribution in an EB weld cavity increases from a temperature well above melting at the specimen surface ($y = 0$) to a peak temperature at the base as predicted.

Referring to Figures 21 and 23, the general trend of the EB welding cavity temperature distribution parallel to the weld is that on the trailing side the temperatures continue to be above melting at further distances from the peak location than on the leading side. This indicates there is more molten metal behind the EB welding cavity than in front. This is caused by the molten metal being forced behind the weld cavity which eventually solidifies during EB welding. The large rate of temperature increase on the leading side for the stainless steel indicates that the slope of the cavity wall on the leading side of the cavity is steeper than that of the trailing side. It appears that the cavity wall slopes on the leading and trailing sides of the cavity are approximately equal for aluminum.

EB Welding Cavity Base Temperature

Average peak temperatures which are assumed to be equivalent to the EB welding cavity base temperatures are compared with base temperature predictions in Figure 29. The measured peak temperature ranges corresponding to spectral emittance ranges of 0.6 to 0.8 for stainless steel 304 and 0.4 to 0.6 for aluminum 1100 were plotted as a function of penetration depth. The predicted temperatures which are represented by the dashed lines were determined from the base temperature analysis for

Figure 29. Comparison of Measured and Predicted Peak Temperatures

elemental iron and aluminum. The measured peak temperatures for stainless steel with a spectral emittance of 0.7 are lower than the base temperature analysis curves with base radii of 0.05 and 0.10 cm by a maximum of 125° and 30°C respectively. Although the curve for a base radius of 0.1 cm shows good agreement with the measured values, it was concluded from fusion zone cross section examinations that a curvature radius of 0.1 cm or greater was highly unlikely.

It is believed that the predicted peak temperatures are high because of the combined effect of using a high surface tension value and not accounting for the presence of chromium in the stainless steel. A lower surface tension value, justified by the fact that S decreases with increasing temperature, would lower the required base vapor pressure and the corresponding base temperature prediction. However, this only accounts for approximately 40°C (2%) as pointed out in the analysis section. Since the base temperature analysis curves are for elemental iron and the actual peak temperature measurements were made on stainless steel 304, the effects of chromium and nickel in the stainless steel must be accounted for. Nickel has approximately the same vapor pressure relation with temperature as does iron, but chromium, which constitutes 20% of the alloy weight, has a higher vapor pressure than iron at a given temperature [11]. At vapor pressures characteristic to those in EB welding cavities, the required temperature for chromium is about 150°C lower than for iron. Assuming that the vapor is a perfect gas, the effect of the chromium would lower the base temperature analysis curves by approximately 30°C. Correcting for the chromium constituent and the lower surface tension would result in the curve with base radius of 0.05 cm being higher than the measured peak temperature for an emittance of 0.7 by approximately 50°C. This corresponds to a maximum difference of 2%.

Effects which would cause the pyrometer to indicate lower than actual base temperatures include the averaging effect of the 1.1 mm diameter target spot and the errors associated with aiming the probe on the peak temperature location. Considering the geometry of the cavity and the techniques involved in aiming the probe, these effects were considered small compared to the uncertainty in the base radius and in the cavity spectral emittance.

For aluminum, the predicted base temperature curves with base radii of 0.05 and 0.10 cm are an average of 170 and 100°C respectively, higher than the measured peak temperature with $\epsilon_\lambda = 0.5$, which corresponds to a maximum difference of 10%. In this case the surface tension used is characteristic of the cavity temperatures involved. Other materials in the Al-1100 (99% aluminum) only constitute a maximum total of one percent of the weight and, therefore, are assumed to have negligible effects on the vapor pressure. All of the other possible factors affecting the results for the stainless steel apply in this case. It was concluded that the base temperature analysis which involves performing force balances on the EB welding cavity is valid for predicting base temperatures as a first approximation.

Peak temperatures are plotted as a function of penetration depth and energy deposition per unit weld length in Figures 30 and 31 respectively. The peak temperature is relatively constant with varying penetration depths and energy depositions. This is because the cavity base pressure is almost completely governed by the base radius of curvature a_B in the dominating first term of the equation for the base vapor pressure (Equation (2) of the Analysis section).

Figure 30. Peak Temperatures as a Function of Penetration Depth

Figure 31. Peak Temperature as a Function of Energy Deposition Per Unit Weld Length.

It is also shown that the average peak temperatures for the aluminum alloys Al-6061 and Al-2024 are significantly lower than for Al-1100 by approximately 150 and 225°C respectively. This is because a lower base temperature is required for the alloys to yield a base pressure equivalent to that of the aluminum Al-1100. Therefore, at a given temperature the vapor pressures of the alloys are higher than those for the aluminum. This is caused by the magnesium and zinc constituents in the Al-6061 (0.25% Zn, 1.0% Mg) and the Al-2024 (0.25% Zn, 1.5% Mg). Even though they constitute only a small fraction, they are significant because their elemental vapor pressures are on the order of atmospheres at characteristic aluminum base temperatures (i.e., 1500°C). The fact that the amount of magnesium is lower in Al-6061 than in Al-2024 and the average peak temperature of the Al-6061 is higher further supports this interpretation.

These extremely volatile elements cause the welding of the alloys to be erratic. The existence of base porosity as shown in Figures 26 and 27 supports this. This also explains the significant percent variation in the peak temperature of these alloys as compared to that of Al-1100 and SS-304 in Table 3.

CONCLUSIONS

Temperature distributions in EB welding cavities were optically measured and compared with predicted values based on a force balance analysis performed on the cavity. The results of this study lead to the following conclusions:

- 1) Surface temperatures in an EB welding cavity increase from a value well above melting at the specimen surface ($y = 0$) to a peak at the base as predicted.
- 2) Typical measured cavity surface temperatures for stainless steel 304 ranged from 1950°C at the specimen surface to 2350°C at the base and from 1300 to 1650°C for aluminum 1100. These values were lower than predicted by a maximum of 5 and 10% for SS-304 and Al-1100 respectively.
- 3) An analysis involving a force balance on the cavity base is valid for predicting base temperatures as a first approximation.
- 4) The average peak temperatures for SS-304, Al-1100, Al-6061, and Al-2024 were measured to be 2300, 1700, 1525, and 1475°C respectively.
- 5) EB welding cavity base surface temperatures are relatively constant with varying penetration depth because they are more strongly dependent on the base curvature instead of the penetration depth.
- 6) The surface tension force plays a more important role in determining the character of an EB welding cavity than does the hydrostatic pressure of the molten metal lining the cavity.
- 7) The peak cavity surface temperatures for Al-6061 and Al-2024 are lower than for Al-1100 because they contain significant

amounts of highly volatile magnesium and zinc. The presence of such alloying elements appears to be responsible for greater peak temperature variation and weld defects such as base porosity.

SUGGESTIONS FOR FURTHER STUDY

During the course of this investigation it was revealed that further study in the following areas would yield valuable information for electron beam welding research:

- 1) Extensive measurements of emittances of molten metals well above their melting temperatures.
- 2) An investigation of the effective emittance which includes the effects of a nonuniform temperature distribution in the EB weld cavity and a more realistic diffuse-specular reflection model.
- 3) Analysis of the effects of the metal vapor in the EB welding cavity on the radiation entering the IR radiation pyrometer probe including radiative absorption, emission, and scattering.
- 4) More accurate determination of typical EB welding cavity dimensions, including the base radius of curvature and the cavity radius variation with respect to depth, would result in more accurate weld cavity temperature predictions.
- 5) Measurements of surface tension of molten metals at temperatures characteristic of EB welding.
- 6) The use of a spectral pyrometer in measuring EB welding cavity temperature distributions would be interesting.

REFERENCES

1. Bakish, R., Handbook of Electron Beam Welding, Wiley and Sons, New York, (1964).
2. James, H. A., "Electron Beam Welding Equipment, Process Parameters, Limitations, and Controls", Electron Beam Metallurgical Processing Seminar, Universal Technology Corporation (Ed.), pp. 2c1-2c65 (1971).
3. Tong, H., "Heat Transfer and Cavity Penetration During Electron Beam Welding", Ph.D. dissertation, University of California, Davis, 1969.
4. Weber, C. M., Funk, E. R., and McMaster, R. C., "Penetration Mechanism of Partial Penetration Electron Beam Welds", Welding Journal, Vol. 52, (2), Research Supplement, pp. 90-s to 94-s (Feb. 1972).
5. Matsuda, F. and Hashimoto, T., "Compilation of the Reports Published on Studies of Electron Beam Welding", Transactions of the National Research Institute for Metals, Japan, (April 1970.)
6. Widdington, R., "The Transmission of Cathode Rays Through Matter", Proc. Roy. Soc., London, A 89, pp. 554-560 (1914).
7. Wells, O. C. and Everhart, T. E., "A Note on Physical Principles Underlying the Formation of the Cavity in Electron Beam Welding", Fourth Annual Meeting Electron Beam Technology, Bakish, R. (Ed.), pp. 105-122 (March 1962).
8. Crawford, C. K., "Electron Beam Machining", Introduction to Electron Beam Technology, John Wiley and Sons, New York, (1962).
9. Schwartz, H., "Mechanism of High Power - Density Electron Beam Penetration", Journal of Applied Physics, Vol. 35, (7), pp. 2020-2029 (July 1964).
10. Mara, G. L., Funk, E. R., McMaster, R. C., and Pence, P. E., "Penetration Mechanism of Electron Beam Welding and the Spiking Phenomenon", Welding Journal, Vol. 53, (2), Research Supplement, pp. 246-s to 251-s, (June 1974).
11. Honig, R. E., "Vapor Pressure Data for the Solid and Liquid Elements", RCA Review, Vol. 23, pp. 567-586 (December 1962).
12. Touloukian, Y. S. (Ed.), Thermophysical Properties of High Temperature Solid Materials, MacMillan Co., New York, (1967).
13. Lynch, C. T. (Ed.), "General Properties", CRC Handbook of Material Science, Vol. 1, CRC Press, Cleveland, Ohio, pp. 105-109, (1974).
14. Lyman, T. (Ed.), "Properties and Selection of Metals", Metals Handbook, Vol. 1, American Society for Metals, Metals Park, Ohio, (1964).

15. Konkol, P. J., Smith, P. M., Willbrand, C. F., and Conner, P., "Parameter Study of Electron Beam Welding", Welding Journal, Vol. 50, (3), pp. 765-776 (November 1971).
16. Weast, R. C., (Ed.), CRC Handbook of Chemistry and Physics, The Chemical Rubber Company, Cleveland, Ohio, (1969).
17. Schauer, D. A., "Emissivity Measurements of Molten Aluminum in Vacuum Using an Infrared Detector", performed at the Lawrence Livermore Laboratory, Livermore, California, unpublished.
18. Siegel, R. and Howell, J., Thermal Radiation Heat Transfer, McGraw-Hill Book Company, New York, pp. 405-409 (1972).
19. Harrach, R. J., Lawrence Livermore Laboratory, Livermore, California, private communication.
20. Sparrow, E. M. and Cess, R. D., Radiation Heat Transfer, Brooks/Cole Publishing Company, Belmont, California, pp. 160-170 (1970).

Appendix A: Force Balance on an EB Welding Cavity with Radius of Curvature a_B .

Figure 32

The following equation was obtained by performing a force balance in the vertical direction on the base as illustrated in Figure 32.

$$(P_v - \rho gh) \pi a_x^2 = 2 \pi a_x S \cos \theta$$

since $a_x = a_B \cos \theta$

$$(P_v - \rho gh) a_B \cos \theta = 2S \cos \theta$$

therefore

$$P_v = \frac{2S}{a_B} - \rho gh \quad (9)$$

This is equivalent to equation (2) in the Analysis section.

Appendix B

Figure 33. Pyrometer Blackbody Calibration Curve

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."