33
1-14-80

WAPD-TM-1428

DOE Research and Development Report

**Temperature and Distortion
Transients in Gas
Tungsten-Arc Weldments**

**S. S. Glickstein
E. Friedman**

MASTER

**Bettis Atomic Power Laboratory
West Mifflin, Pennsylvania 15122**

October 1979

**Prepared for the
U.S. Department of Energy
By Westinghouse Electric Corporation
Under Contract No. DE-AC11-76-PN00014**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TEMPERATURE AND DISTORTION TRANSIENTS IN GAS TUNGSTEN-ARC WELDMENTS

S. S. Glickstein
E. Friedman

October 1979

Contract No. DE-AC11-76-PN00014

Printed in the United States of America
Available from the
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTE

This document is an interim memorandum prepared primarily for internal reference and does not represent a final expression of the opinion of Westinghouse. When this memorandum is distributed externally, it is with the express understanding that Westinghouse makes no representation as to completeness, accuracy, or usability of information contained therein.

BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA 15122

Operated for the U. S. Department of Energy
by Westinghouse Electric Corporation

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States, nor the United States Department of Energy, 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.

TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	1
II. EXPERIMENT	4
III. THERMAL MODEL	4
IV. EXPERIMENTAL RESULTS	7
A. Temperature Measurements	7
B. Distortion of Weld Plates	7
C. Determination of Emissivity	8
V. COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS	9
A. Plate Temperatures and Weld Bead Shape	9
B. Plate Distortion	11
VI. ANALYSIS OF PLATE THICKNESS EFFECTS	13
VII. ANALYSIS OF WELD SPEED EFFECTS	14
VIII. CONCLUSIONS	16
IX. REFERENCES	17

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1a.	Experimental Arrangement for Positioning Weld Plates in Fixture	28
1b.	Location of Thermocouple (TC) and Direct Current Displacement Transducers (DCDT) on Underside of Weld Sample (TC No. 1 Top Surface)	28
1c.	Positions of Displacement Transducers in Weld Fixture	28
2.	Calibrated Voltage Output as a Function of Deflection for Direct Current Displacement Transducer (DCDT) No. 1	29
3.	Typical Temperature and Distortion Transient Data from Thermocouple and Displacement Transducer Channels	30
4.	Location of Residual Distortion Measurements, δ	31
5.	Weldment Configuration	32

LIST OF FIGURES (Cont)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
6.	Typical Finite Element Mesh	33
7.	Distortion of Thin Weld Plates	34
8.	Typical Experimental Deflection Transients as Recorded at Displacement Transducer Positions Noted in Figure 1. (1 mil = 0.0254 mm)	35
9.	Normal Total Emittance for Various Surface Conditions of Oxidized Stainless Steels as a Function of Temperature ⁽¹²⁾	36
10.	Measured and Calculated Temperatures of 1.59 mm Thick Alloy-600 Plate Initially at 1000°C Cooled in Air	37
11.	Measured and Calculated Temperatures of 3.18 mm Thick Alloy-600 Plate Initially at 1000°C Cooled in Air	38
12.	Measured and Calculated Temperatures of 6.35 mm Thick Alloy-600 Plate Initially at 1000°C Cooled in Air	39
13.	Calculated and Measured Temperature Transients at Thermocouple Positions TC1, TC2, TC3, and TC4 Noted in Figure 1	40
14.	Calculated and Measured Peak Temperatures. Plate Thickness = 1.5 mm, Weld Speed = 2 mm/s, $T(70)$ = Temperature of all Thermocouples After 70 Sec, T_m = Melting Temperature	41
15.	Calculated and Measured Peak Temperatures. Plate Thickness = 3.18 mm, Weld Speed = 2 mm/s, $T(70)$ = Temperature of all Thermocouples After 70 Sec, T_m = Melting Temperature	42
16.	Calculated and Measured Peak Temperatures. Plate Thickness = 6.35 mm, Weld Speed = 4.133 mm/s	43
17.	Calculated and Measured Peak Temperatures. Plate Thickness = 6.35 mm, Weld Speed = 2.067 mm/s	44
18.	Calculated and Measured Weld Bead Dimensions Weld Speed = 2 mm/s, Plate Thickness = 1.59 mm	45
19.	Calculated and Measured Weld Bead Dimensions Weld Speed = 2 mm/s, Plate Thickness = 3.18 mm	46
20.	Calculated and Measured Weld Bead Dimensions, Weld Speed = 2.067 mm/s, Plate Thickness = 6.35 mm	47
21.	Calculated and Measured Weld Bead Dimensions, Weld Speed = 4.133 mm/s, Plate Thickness = 6.35 mm	48

LIST OF FIGURES (Cont)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
22.	Effect of Arc Current and Plate Thickness h , on Heat Input Distribution Parameter r . Weld Speed = 2 mm/s	49
23.	Photographs of Argon Arc Incident on Cooled 6.35 mm Thick Alloy-600 Plate as a Function of Time After Arc Ignition, $I = 50A$.	50
24.	Photographs of Argon Arc Incident on Cooled 6.35 mm Thick Alloy-600 Plate as a Function of Time After Arc Ignition, $I = 100A$.	51
25.	Calculated "Inherent Angular Change" δ , for a Bead on Plate Weld as a Function of "Inherent Shrinkage Parameter" X	52
26.	Effect of Plate Thickness on Weld Penetration for a Point Source, Closed-Form Solution	53
27.	Effect of Weldment Thickness on Weld Bead Dimensions. Heat Input = 450W, Weld Speed = 2 mm/s, Heat Input Distribution Parameter $r = 4.8$ mm	54
28.	Effect of Weldment Thickness on Weld Bead Dimensions for Different Heat Input Parameters r . Heat Input Per Unit Thickness (Q/h) = 142 kW/m. Weld Speed = 2 mm/s	55
29.	Variation of Peak Temperatures with Weld Speed. Heat Input (Q/v) = 218 kJ/m	56
30.	Variation of Weld Bead Dimensions with Weld Speed. Heat Input (Q/v) = 218 kJ/m	57
31.	Effect of Arc Current and Weld Speed on Distribution of Heat Input	58

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
1.	Summary of Welding Conditions	20
2.	Thermal Response of Test Welds	21
3.	Residual Distortion of 1.59 mm (1/16 in) Thick Weld Plates Weld Speed = 2 mm/sec (4.72 ipm)	23
4.	Residual Distortion of 3.18 mm (1/8 in) Thick Weld Plates Weld Speed = 2 mm/s (4.72 ipm)	24

LIST OF TABLES (Cont)

<u>Table</u>	<u>Title</u>	<u>Page</u>
5.	Residual Distortion of 6.35 mm (1/4 in) Thick Weld Plates for Varying Currents (I) and Weld Speeds (v)	25
6.	Summary of Measured Plate Distortion in Alloy-600 Weld Tests	26
7.	Calculated Inherent Distortion (δ) for Typical Values of Bead-on-Plate Welding Conditions Studied	27

An analysis and test program to develop a fundamental understanding of the gas tungsten-arc welding process has been undertaken at the Bettis Atomic Power Laboratory. The purpose of the program is to develop techniques to determine and control the various welding parameters and weldment conditions so as to result in optimum weld response characteristics. These response characteristics include depth of penetration, weld bead configuration, weld bead sink and roll, distortion, and cracking sensitivity.

This report documents the results of that part of the program devoted to analytical and experimental investigations of temperatures, weld bead dimensions, and distortions for moving gas tungsten-arc welds applied to Alloy 600 plates.

TEMPERATURE AND DISTORTION TRANSIENTS IN GAS TUNGSTEN-ARC WELDMENTS

S. S. Glickstein
E. Friedman

I. INTRODUCTION

Considerable effort has been expended on developing effective welding techniques for a large number of metals and alloys and on identifying and characterizing the various problems that result. Work done in these areas has been overwhelmingly experimental, although some attempts have been made to develop and apply analytical models to explain and predict the thermal and mechanical response of weldments. In most analyses, the models used to simulate the welding process^(1,2) have been extremely simplified, resulting in a number of inherent limitations. Utilization of the digital computer has eliminated many of these limitations. While solution methods that do not use numerical techniques can be useful, computer simulation of, for example, the welding thermal cycle permits consideration of such phenomena as temperature-dependent material properties, finite distribution of the heat source, phase-change-induced latent heat, and irregular weldment and weld bead shapes.

Using finite difference and finite element approaches, a number of authors (see, for example, ^(3,4,5)) have carried out numerical simulations of the welding process. In all these works, the approach has been to develop the analytical

techniques and then confirm numerical results with experimental data. The potential now exists to extend the scope of numerical welding analysis beyond the confirmation stage.

Comprehensive studies of the gas tungsten-arc welding (GTAW) process, using both experimental and analytical techniques, are currently in progress at the Bettis Atomic Power Laboratory. The ultimate goals of these studies are to:

1. Establish criteria and guidelines for effective welding procedures.
2. Identify the root causes of welding problems.

To meet such broad objectives, a systematic approach to understanding the welding process must be followed. This report covers a portion of an overall investigation that works toward accomplishing the following:

1. For varying welding conditions, establish the magnitude and distribution of heat input from the welding arc to the weldment.
2. Having established the heat input to the weldment, predict:
 - a. Final weld bead configuration;
 - b. Temperature transients in the heat-affected zone and the surrounding region; and
 - c. Transient and residual distortions and stresses in the workpiece resulting from the welding temperature transients.

Successful development of analytical techniques to calculate these weld response characteristics would make it possible (1) to perform metallurgical studies to accurately predict the structure and mechanical properties of a weld joint and (2) to better characterize and predict weld defects, such as cracking and porosity, that occasionally result from the welding process.

The approach for the experimental portion of the study is to run test welds on moderately thick flat plates, analyze the tests, and interpret the data to determine the nature of heat transfer in the weldment. The analytical portion consists of using the finite element method of analysis to calculate temperatures resulting from the same conditions used for the test welds. Preliminary work done with both stationary and moving GTAW sources has been reported⁽⁶⁾, and a more comprehensive analysis has been initiated. The first phase of the latter effort--an analysis and test program dealing with stationary arcs--has been

completed⁽⁷⁾. Analytical and experimental temperature data were correlated for stationary arc welds and a comprehensive parametric study was performed. This study provided quantitative data on how four key welding variables interact to influence the depth of penetration and the width of the weld bead. These variables are (1) the magnitude of the heat input from the arc, (2) the area of the weldment surface upon which the heat is applied, (3) the duration of heating (akin to the reciprocal of the welding speed for moving arcs), and (4) the weldment thickness.

This report describes the second phase of the GTAW analysis and test program. This phase deals with the thermal response of weldments formed by applying moving GTA heat sources to plates of various thicknesses. The welds studied were partial and full penetration welds in 6.35 mm (1/4 in), 3.18 mm (1/8 in), and 1.59 mm (1/16 in) NiCrFe Alloy 600 plates. Weld speeds of 2.067 mm/s (4.88 ipm) and 4.133 mm/s (9.76 ipm) and current ranging from 50 A to 150 A were employed for the 6.35 mm (1/4 in) thick weldments, while constant weld speed of 2.0 mm/s (4.72 ipm) and current varying between 50 A and 150 A were used for the other two plate thicknesses. Both the transient thermal response and dimensional changes (distortions) were examined for the various conditions. The analytical and test results show how the weld bead dimensions are influenced by (1) the magnitude and distribution of the heat input from the welding arc and (2) the weld speed. The results can also be used to derive quantitative relationships between controllable welding parameters (e.g., current, weld speed, and weldment thickness) and those variables (e. g., heat input magnitude and distribution) that influence penetration and bead width characteristics.

The following sections of this report discuss in detail the aspects of the analysis and test program described above. Section II presents a description of the experimental techniques for measuring the transient temperatures and distortions. Section III briefly discusses the analytical thermal model of the weld process. Sections IV through VII present the results of the parametric studies in which the effects of varying weld current, plate thickness, and weld speed on the temperature and weld bead configuration are assessed experimentally and analytically.* Section VIII summarizes results of this investigation, discusses the limitations of the present analytical model, and outlines plans for further development effort.

*The weld bead dimensions are calculated directly from the peak temperature distribution, since the weld bead is defined as the region of the weldment in which the peak temperature exceeds the melting point.

II. EXPERIMENT

The test welds discussed in this report used the experimental arrangement for measuring plate temperatures as described by Glickstein, et al ⁽⁶⁾. The welds were made automatically using a gas tungsten-arc welding torch attached to a side beam welding fixture. The plates were held in place by four set screws as shown in Figure 1a. This eliminated the external heat sink that the usual clamping mechanism would have introduced. Chromel-alumel thermocouples were spot welded to the top and bottom surfaces of the plate at the locations shown in Figure 1b. The transient temperature response was measured using four channels of an eight channel recorder. The weld current and total voltage were recorded simultaneously, and the arc voltage was inferred from estimates of the line cable and electrode voltage drop ⁽⁶⁾.

Transient distortions of the weld plates were measured using four direct current, standard 24 V displacement transducers (DCDT) positioned as shown in Figure 1c. Each transducer was separately calibrated prior to the experiment. A typical calibration curve is shown in Figure 2. The transient distortion response during welding was displayed using the remaining four channels of the eight channel chart recorder. Typical output from the eight channel recorder is shown in Figure 3. A data reduction computer program analyzed the measurements and corrected them for initial mechanical offset, background temperature, transducer sensitivity, and initial time offset. The residual distortion of the entire weld plate was also determined by setting the plate on a flat block and measuring the height at locations along the center of the plate and along the edges at the positions marked in Figure 4.

III. THERMAL MODEL

A complete description of the thermal model for the moving weld was reported by Friedman ⁽⁸⁾. This section presents a summary of the salient features of the model as applied to the bead-on-plate arc weld presently under consideration. Material composition and properties of NiCrFe Alloy 600 are used ⁽⁹⁾. The weld bead is applied on a straight line at constant speed v , as indicated in Figure 5.

Calculation of the transient temperature distribution is based on attainment of quasi-stationary conditions. The temperature at any point is expressed functionally as:

$$T(x_1, x_2, x_3, t) = T(x_1, x_2, x_3 - vt) \quad (1)$$

Thus, given the transient temperature distribution at any one section (say $x_3 = 0$) of the weldment normal to the weld direction, the temperature at any other section is determined by an appropriate shift in the time scale as follows:

$$T(x_1, x_2, x_3, t) = T(x_1, x_2, 0, t - x_3/v) \quad (2)$$

Therefore, the problem is reduced to finding the two-dimensional unsteady temperature field at a section normal to the weld line. A planar analysis may be used for this purpose when the weld speed, relative to a characteristic thermal diffusion rate for the material, is sufficiently high that the amount of heat conducted ahead of the weld torch is small relative to the total heat input. In this case, the net heat flow across any infinitesimally thin slice of the weldment normal to the weld line is assumed negligible relative to heat diffused within the slice itself. This assumption is made for the weld speeds presently considered.

The basic input parameters required for thermal analysis of a weld are the magnitude of the heat input from the welding arc, the distribution of that heat on the surface of the weldment, and the weld speed. The magnitude of heat input (Q) is found from the formula:

$$Q = \eta EI \quad (3)$$

where η is the arc efficiency, E is the arc voltage, and I is the current.

Following the approach of Pavelic, et al⁽¹⁰⁾, the heat from the arc is, at a given point in time, assumed to be deposited on the weldment surface as a radially symmetric normal distribution function. Letting r be the distance from the center of the heat source, the heat flux $q(r)$ acting on the surface is defined by

$$q(r) = \frac{3Q}{\pi r^2} \exp\left[-3(r/\bar{r})^2\right], \quad (4)$$

where $\bar{r}$ is a characteristic radial dimensional distribution parameter that defines the region in which 95 percent of the heat flux is deposited. If $t = 0$ is defined as the time at which the center of the heat source passes over the section $x_3 = 0$, the heat flux distribution on the surface of this section is given by

$$q(x_1, t) = \frac{3Q}{\pi \bar{r}^2} \exp\left[-3(x_1/\bar{r})^2\right] \exp\left[-3(vt/\bar{r})^2\right] \quad (5)$$

This formula defines the contributions of the three welding heat input variables Q , $\bar{r}$, and v to the heat input distribution.

Heat is assumed lost to the surroundings by radiation and by natural convection on those surfaces not subject to direct heating by the arc. These heat losses are designated as q_r and q_c , respectively, and are determined from the following relations:

$$q_r = \epsilon \sigma (T - T_o)^4 \quad (6)$$

$$q_c = h(T - T_o)^{1.25} \quad (7)$$

where

ϵ = emissivity

σ = Stefan Boltzman constant

h = convection coefficient

T = surface temperature

T_o = ambient temperature

The emissivity (ϵ) of the Alloy 600 surface was determined experimentally and is discussed in detail in Section IV.C. The average value for the laminar flow heat transfer convection coefficient (h), for the top and bottom surfaces of the weld plate was calculated to be $1.566 \text{ W/m}^2 \cdot \text{K}^{5/4}$ (11).

Details of the finite element method for transient heat conduction and its application to welding thermal analysis have been given by Friedman⁽⁸⁾. The finite element mesh system used for the moving GTAW thermal analyses is shown in Figure 6. Due to symmetry about the weld centerline, only half the section at $x_3 = 0$ need be analyzed. A fine mesh spacing is introduced near the centerline due to very high temperature gradients in this region.

IV. EXPERIMENTAL RESULTS

A. Temperature Measurements

Using the arrangement shown in Figure 1, thermocouple readings were obtained on 21 test welds for various combinations of plate thickness, arc current and weld speed. A summary of the welding conditions for each test is given in Table 1.

The thermal response is characterized by peak temperatures measured at the four thermocouple locations shown in Figure 1 and by the weld bead width and depth measured from photomicrographs of weldment cross-sections. These data are given in Table 2. Where a temperature value is omitted, either a malfunction of the electronics occurred or the thermocouple broke during the weld cycle. Where a temperature value is enclosed in brackets, the thermocouple was imbedded in the molten weld puddle. For these cases, the position of the thermocouple was uncertain due to possible movement of the wire, or the temperature range of the chromel-alumel wire may have been exceeded. Other questionable data have been indicated by an asterisk. For the remaining temperature recordings, the uncertainty is estimated to be on the order of $\pm 50^{\circ}\text{C}$. This error is mainly attributed to the limitation inherent in reading the voltage from the strip chart recording and to the uncertainty of the thermocouple position.

B. Distortion of Weld Plates

The residual distortions (Figure 7) of the 1.59 mm (1/16 in), 3.18 mm (1/8 in) and 6.35 mm (1/4 in) thick plates are presented in Tables 3 through 5. Transverse deflections on the order of 0.1 mm (0.004 in) to 0.2 mm (0.008 in) were measured for the 3.18 mm and 6.35 mm thick plates. Transverse deflections for the 1.59 mm weld plates were as large as 1 mm at a welding current of 75 A. For the thin (1.59 mm) plates, the transverse shrinkage induced distortions were of a much smaller magnitude than the longitudinal distortions. In addition, the longitudinal distortions were opposite in direction to those that would have been induced by shrinkage.

The strip chart recordings of the transient distortions (Figure 8) indicate that the bulk of longitudinal distortion of the thin (1.59 mm) plates occurred subsequent to termination of heat applied from the welding arc and while the plates were being cooled. This response indicates a buckling phenomenon.

It was initially thought that residual stresses that existed within the plates prior to welding may have been of sufficient magnitude to initiate buckling. To test this hypothesis, several plates were annealed at 1000°C (1830°F) prior to welding; distortions of the same magnitude and direction still occurred, indicating that the buckling occurred independently of residual stresses. Bead-on-plate welds were then made without any holddown fixture, that is, in a free position resting on two narrow rails; again, distortions of the same magnitude and direction occurred. It was concluded, therefore, that the buckling was weld-induced. Though weld-induced buckling of thin plates has previously been characterized⁽²⁾, there is no obvious reason why all plates buckle in the same direction. Geometric constraints in actual weldments would probably prevent such buckling.

A summary of the measured transverse and longitudinal residual distortions is presented in Table 6. Typical transient deformation recordings of a test plate are shown in Figure 8.

C. Determination of Emissivity

Input to the analytical model for determining the transient temperature distribution throughout a weldment includes characterization of the rate of heat loss from the surfaces of the weldment during cooldown. Surface conditions result in large variations in emissivity⁽¹²⁾, as indicated in Figure 9. As a result, radiation losses can contribute a relatively large uncertainty to the surface heat loss. To reduce this uncertainty, several test plates were heated in an oven for approximately 30 minutes at a temperature of 1000°C (1830°F). Each plate was quickly removed from the oven and allowed to cool in room temperature air while the temperature at a point near the center of the top surface was recorded as a function of time.

Plate cooldown was analyzed numerically using the same model employed to evaluate welding temperatures⁽⁸⁾. Various values of emissivity were assumed in the calculations in order to obtain a best estimate for use in the welding analysis calculations. The experimental and analytical results for the three plate thicknesses are shown in Figures 10 through 12.

As a result of these tests, the emissivity of the 1.59 mm (1/16 in) and 3.18 mm (1/8 in) Alloy-600 plates was taken to be 0.5 for all the analytical

studies. An emissivity of 1.0 was used for the analysis of the 6.35 mm (1/4 in) thick plates, which is in agreement with the experimental data for a plate of this thickness. Despite these results, there is no obvious reason why the emissivity for the thick plate should differ from that for the thin plates.

V. COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

A. Plate Temperatures and Weld Bead Shape

For each combination of weld speed, arc current, and plate thickness, the magnitude Q of the heat input to weld from the arc was varied until computed and measured peak temperatures were in reasonably good agreement. Satisfactory agreement between computed and measured temperatures and reasonable values of arc efficiency ($0.75 < \eta < 0.80$) were obtained for the nominal arc currents listed in Table 1. Typical temperature vs. time curves are plotted in Figure 13.

Once the heat input magnitude was fixed for a given speed, plate thickness, and current, the value of the heat input distribution parameter $\bar{r}$ was varied to (1) determine the effects of varying $\bar{r}$ on the peak temperatures and the weld bead dimensions, and (2) simulate the actual heat input distribution by determining the value of $\bar{r}$ that produces good agreement between computed and measured weld bead dimensions. Thus, by correlating analysis and test results, quantitative determinations of the effects of various welding parameters can be made. In this case, the heat input magnitude and distribution, which determine to a large degree the weld bead shape and penetration characteristics, were correlated for prescribed arc currents, plate thicknesses, and weld speeds.

Figures 14 through 17 show plots of changes in computed peak temperatures at the four thermocouple locations as the heat distribution parameter $\bar{r}$ is varied. The figures also show the range of measured peak temperatures corresponding to each combination of plate thickness, current, and weld speed. For the 3.18 mm and 6.35 mm (1/8 in and 1/4 in) plates for which full penetration was not attained, the calculated peak temperatures at location T2 are higher than the measured values. This is attributed to the inability of the analytical model to account for net heat flow in the weld direction. However, computed and measured temperatures at the other three locations are in good agreement.

For the range of parameters used, a wider distribution of the heat input (increased $\bar{r}$) increases temperatures at location T1 on the top surface of the

weldment. Temperatures at locations T2, T3, and T4 on the bottom surface decrease as the heat input distribution is widened. This effect decreases in magnitude as distances from the weld centerline increase. Location T4 is sufficiently removed from the weld centerline that only the magnitude, and not the distribution, of the heat input determines the temperature response at this location. As a general conclusion, the temperatures at the thermocouple locations, except for T2, are relatively insensitive to the distribution parameter $\bar{r}$.

Figures 18 through 21 show plots of changes in computed weld bead dimensions as the heat input distribution parameter ($\bar{r}$) is varied for the three plate thicknesses. Variations of weld bead width and depth (or width at the bottom surface of the plate for full penetration welds) with $\bar{r}$ are plotted for the various heat input magnitudes considered, together with the range of measured dimensions for the corresponding nominal arc currents. For each case, the intersection of the curve generated from computed data with the line representing the mean value of the measured dimensions yields the estimated value of $\bar{r}$ corresponding to the given welding parameters (current, speed, weld thickness). Values of this distribution parameter can be deduced from both weld bead width and weld bead depth (or weld bead bottom width for full penetration welds) data, and are presented in Figure 22 as a function of arc current for the three plate thicknesses studied (1.59, 3.18, 6.35 mm).

The following conclusions can be drawn from the results presented in Figure 22:

1. The heat input distribution from the arc to the weldment becomes more diffuse ($\bar{r}$ increases) as the current increases for each of the three plate thicknesses studied. This is consistent with earlier visual observations and photographic studies of the arc⁽¹³⁾.
2. The heat input distribution parameter ($\bar{r}$) increases as the plate thickness decreases. The reason for this result is not immediately obvious. One possible explanation is that for a fixed weld current, decreased weldment thickness results in higher temperatures and an enlarged puddle. An increased puddle size may then influence the contraction of the arc and change the configuration of the heat source. To check this hypothesis, photographs of a stationary arc were taken during the time interval from arc initiation to the time of maximum

weld puddle diameter (prior to arc extinction). Typical results for 50 A and 100 A argon arcs applied to 6.35 mm (1/4 in) Alloy 600 plates are shown in Figures 23 and 24. Careful observations of a number of such photographic tests revealed no significant variation in arc configuration with time as the puddle diameter increased. From these visual studies it does not appear likely that the heat input distribution from the arc changed as the weld puddle width changed, although tests on plates of varying thickness would be required to confirm this. A second possible explanation for the apparent $\bar{r}$ variation may be associated with weld puddle shape changes and liquid metal circulation. As has been documented^(6,7), thermal conduction controls the flow of heat in solid weldment material, but is only one of the heat transfer mechanisms present in the molten weld puddle. Effects of arc pressure and weld puddle surface tension have been considered analytically for stationary arcs, and their effects on weld penetration have been shown to be significant⁽¹⁴⁾. The effects of weld puddle circulation have yet to be introduced. These combined effects, when included in the analytical heat transfer model, could significantly alter the calculated depth and width of the weld bead. Thus, the apparent variation in $\bar{r}$ as the plate thickness is varied may be due to not including the effects of weld puddle shape changes and liquid metal circulation in the analytical thermal model for moving welds.

For the 3.18 mm thick weld plates, the use of a single value of the heat input distribution parameter ($\bar{r}$) at a fixed current does not produce satisfactory agreement between experimental and analytical data for both weld bead width and depth. Though single values of $\bar{r}$ were found to fit the data for the 6.35 mm and 1.59 mm thick weld plates, the need to include both circulation and weld puddle shape change effects in the analysis remains evident.

B. Plate Distortion

Based on extensive experimental and analytical studies, formulas have been proposed⁽²⁾ for predicting various types of distortions in weld plates. From

the tables presented by Masubuchi⁽²⁾, the inherent angular change δ (See Figure 25) in radians for bead-on-plate welds can be represented by the following empirical equation:

$$\delta = 0.131 \times 10^{-6} X^{2.5} \exp(-0.01 X) \quad (8)$$

X is called the inherent shrinkage parameter and is given by

$$X = \frac{I}{h} (vh)^{-1/2} \quad (9)$$

where

I = welding current in A,

h = thickness of weld plate in cm,

v = welding speed in cm/s.

The above formulation has been characterized for use with Illumenite type welding rods 4 mm (0.157 in) in diameter. The parameters in equation (8) are typical, and vary slightly according to rod type and diameter.

The inherent angular change as a function of the inherent shrinkage parameter given by equation (8) has been plotted in Figure 25. For small values of X (that is, for low heat input, or for depth of penetration negligible compared to plate thickness) the exponential term in equation (8) can be approximated by the value 1.0. Under these conditions, distortion is small and is proportional to $X^{2.5}$. As X increases, the distortion reaches a maximum and then decreases as full weld penetration is achieved. Once the weld has fully penetrated and the weld bead is rectangular in shape, the transverse shrinkage stresses become uniform through the weldment thickness. In this case, the exponential term in equation (8) is dominant, and distortion is again small. Table 7 summarizes the welding conditions for the bead-on-plate welds for the three thicknesses of plates studied and lists the inherent distortion values determined from equation (8). The calculated results are in relatively good agreement with experimental data for the thick (6.35 mm) plate condition; however, the calculated results show zero distortion for the thinner plates, which is contrary to the experimental data.

Since the use of empirical formulas is not satisfactory for predicting weld-induced distortions, finite element methodology has been introduced⁽⁸⁾ to

calculate distortions resulting from the welding thermal cycle. The mechanical response model is used to calculate transient and residual stresses as well as distortions. Typical results of distortion and stress calculations for bead-on-plate welds and for omega seal welds have been presented^(8,15). However no calculations have been made for the measured distortions discussed in this report. Limitations inherent in the analytical treatments thus far carried out center around the two-dimensional nature of the computer program. This prevents calculation of longitudinal distortions. In addition, convergence problems often arise in the present nonlinear elastic-plastic materials behavior formulation. Further computer program development work is planned to alleviate these difficulties.

VI. ANALYSIS OF PLATE THICKNESS EFFECTS

In this section, an analytical study of the effects of plate thickness on the weld bead dimensions is discussed. For a part of this study, a moving point source of heat (Q), is applied to the surface of a plate. The plate is assumed infinite in extent. The closed form solution for the temperature T within the plate is given by the following equation:

$$T(x,y,z,t) = \frac{Q}{2\pi k} \exp \left[-\frac{v(x-vt)}{2\kappa} \right] \sum_{n=-\infty}^{\infty} \left\{ \left[\exp \left(\frac{-vr_n}{2\kappa} \right) \right] / r_n \right\} \quad (10)$$

where

$$r_n = \left[(x-vt)^2 + y^2 + (z+2nh)^2 \right]^{1/2}$$

Q = heat input

k = conductivity

v = weld speed

t = time

κ = diffusivity

h = plate thickness.

Material properties k and κ are independent of temperature, and latent heat due to phase change is not included. The physical data used for the calculations are representative of Alloy 600.

Figure 26 shows curves of heat input vs. resultant depth of penetration for different plate thicknesses at a given weld speed. A small variation in plate thickness can make the difference between a full penetration and a partial

penetration weld, as can be noted by comparing the results for 3.05 mm (0.120 in) and 3.19 mm (0.125 in) thick plates at a heat input of approximately 800 W.

This important observation is further illustrated in Figure 27, in which the depth and width of the weld, calculated using the finite element model, are plotted as functions of plate thickness. For purposes of illustration, the heat input magnitude (Q), heat input distribution parameter ($\bar{r}$), and weld speed (v) are fixed at the values noted on Figure 27. As full penetration is approached, an extremely rapid increase in penetration is observed for small changes in plate thickness. Once full penetration is achieved, the weld puddle tends rapidly toward a rectangular shape, as indicated in Figure 27 by the rapid approach of the bottom surface weld width toward the top surface weld width as the thickness is decreased.

Finite element analyses of welding temperatures and weld bead configurations have also revealed some of the limitations inherent in using relatively simple closed-form solutions to predict the thermal cycle. For example, the solution obtained using a line source of heat distributed uniformly through the thickness of an infinite plate has often been used to simulate the thermal response in thin weld plates⁽¹⁶⁾. In addition to the limitations of using constant material properties and neglecting latent heat effects, the line source approach employs a heat input per unit thickness Q/h , rather than the heat input Q , as input. A full penetration weld with uniform width through the thickness is, therefore, obtained for prescribed Q/h . Finite element solutions for weld width and depth for a fixed Q/h of 142 kW/m and varying plate thickness h are shown in Figure 28, for $\bar{r} = 4.8$ and 6.0 mm (0.189 and 0.236 in). Figure 28 also shows the full penetration weld width predicted using the line source solution. The inadequacy of the line source solution is evident.

VII. ANALYSIS OF WELD SPEED EFFECTS

This section discusses the results of analytical study of the effects of weld speed on the bead dimensions and peak temperatures. The study was performed using the finite element analyses previously discussed. The total heat input per unit length of weld (H) was maintained constant at 218 kJ/m, while the weld speed (v) was varied between 2.067 and 12.4 mm/s (4.88 and 29.27 ipm). The magnitude of the heat input (Q) was varied to maintain the value of $H = Q/v$ constant. Calculations were carried out for values of 3.6 and 4.8 mm (0.142 and 0.189 in) for the distribution parameter $\bar{r}$. Figures 29 and 30 show the results for peak temperatures and bead dimensions, respectively.

As shown in Figure 29, a wider distribution of the heat input ($\bar{r} = 4.8$ mm) produces increased temperatures at the top surface of the weldment (location TC1) and lower temperatures on the bottom surface (locations TC2, TC3, and TC4; see Figure 1). The effect of heat input distribution decreases as distances from the centerline of the weld increase until, at location TC4, the effect of heat input distribution on temperature is negligible.

Increased weld speeds tend to produce higher temperatures, especially at locations (TC1, TC2) in close proximity to the region in which heat is deposited via the arc; this effect, however, diminishes at very high speeds. At sufficiently high weld speeds (relative to the rate of thermal diffusion) energy is deposited on the surface of any section of the weldment normal to the weld direction at such a high rate that the heat input is well approximated by an instantaneous deposition of heat with an intensity $H = 218$ kJ/m. Further increases in weld speed will not alter the instantaneous nature of the heat input, and the thermal response becomes dependent just on the heat input per unit length of weld and not on the weld speed.

This is further illustrated in Figure 30, where the rates of increase of weld bead width and depth at relatively high weld speeds are much less than those at lower speeds. Superior penetration and depth-to-width ratios are obtained for higher welding speeds, though higher weld speed must be accompanied by higher arc current in order to maintain the intensity ($H = Q/V$) of the heat source. For the entire range of weld speeds considered, a more concentrated source of heat produces a greater depth of weld bead penetration. On the other hand, for the range of the heat input distribution parameter ($\bar{r}$) considered in this study, a more diffuse source of heat produces greater weld bead widths if the weld speed is sufficiently high (in this case, $v > 6.2$ mm/s (14.7 ipm)). The latter relationship is due to heat being deposited at a higher rate for high weld speeds, thus heating a relatively larger area of the weld surface to temperatures that exceed the melting point. As discussed in a previous study on stationary arc welds⁽⁷⁾, sufficiently large values of the distribution parameter ($\bar{r}$) for a fixed magnitude of heat input will result in a reduction of bead width.

The effect of arc current on the heat input distribution was deduced from both width and depth correlations. Figure 31 shows the results for the two weld

speeds considered. These results indicate that heat input from the arc to the weldment becomes more diffuse ($\bar{r}$ increases) as the current increases; also, values of $\bar{r}$ are higher at the lower speeds. These results are consistent with visual observation and photographic studies of the arc⁽¹³⁾.

VIII. CONCLUSIONS

The analytical and experimental investigation of temperatures, weld bead dimensions, and distortions for moving gas tungsten-arc welds applied to various thickness Alloy 600 plates has produced the following results:

1. By applying a reasonable estimate of the arc efficiency ($0.75 < \eta < 0.80$), the welding thermal analysis model produces a thermal cycle that is in reasonably good agreement with thermocouple data for wide ranges of arc current and plate thickness. Differences between calculated and measured results can be attributed primarily to the two-dimensional nature of the thermal analysis. This restriction can be relaxed by modification of the computer program.
2. The magnitude of the heat input from the arc to the workpiece can be inferred by proper selection of the arc efficiency. The distribution of the heat input on the surface of the weldment is, however, a priori unknown. The heat input distribution, characterized by the dimensional parameter $\bar{r}$, was studied for its effect on temperature and weld bead dimensions. The effect of $\bar{r}$ on temperature is small as the distance from the weld centerline increases. However, the effect of $\bar{r}$ on weld bead dimensions, which depend on peak temperature distributions near the weld centerline, is substantial.
3. Computed and measured weld bead dimensions were correlated to determine how the heat input distribution ($\bar{r}$) is affected by arc current and plate thickness. For each plate thickness, $\bar{r}$ increased with increasing current. This is in agreement with photographic observations of the welding arc. The distribution parameter $\bar{r}$, however, decreased as the plate thickness decreased. This was unexpected and may have been due to the fact that the analytical thermal model used did not include the effects of weld puddle shape changes and liquid metal circulation. Considerably more work must be done in analyzing weld puddle circulation in order to better understand the actual heat transfer process in the puddle.

4. Evaluation of plate distortion data indicated that calculated results using empirical formulas are in reasonable agreement with experimental data for thick plate conditions but could not be used for thin plates. Although analytical models of weld-induced distortions have been formulated, no analytical treatment of distortions for the present series of GTA test welds was carried out. The two-dimensional nature of the existing computer program prevents calculation of longitudinal distortions. Furthermore, recurrent convergence problems in the nonlinear elastic-plastic materials behavior formulation have inhibited the attainment of distortion solutions using reasonable amounts of computer time. Further computer program development work is planned to alleviate these difficulties.
5. Penetration characteristics improve as weld speed increases for specified amounts of thermal energy input per unit length of weld. An increase in weld speed, however, entails an accompanying increase in arc current.
6. The finite element welding thermal analysis method is very well suited for (1) determining the interrelationship of heat input magnitude, heat input distribution, and weld speed, and (2) predicting the effect of that interrelationship on the temperature transients and weld bead dimensions. The potential exists to use the method to estimate the combination of welding and geometric parameters that will produce an optimum weld configuration. However, analysis and testing should be undertaken to include the effects of arc pressure, puddle surface tension and weld pool motion in the thermal analysis model. Initial work on this effort has been reported⁽¹⁴⁾.
7. Continued study of the physics of the gas tungsten-welding arc is required in order to understand how to control the magnitude and distribution of the heat input, as well as the arc pressure, by varying such welding parameters as current, voltage, electrode shape, arc gap, shielding gas, and insert additives. The effects of shielding gases and gas impurities on the welding arc have recently been reported⁽¹⁷⁾.

IX. REFERENCES

1. Myers, P. S., Uyehara, O. A., and Borman, G. L., "Fundamentals of Heat Flow in Welding," Welding Research Council Bulletin No. 123, July 1967.

2. Masubuchi, K., "Control of Distortion and Shrinkage in Welding,"
Welding Research Council Bulletin No. 149, April 1970.
3. Hibbitt, H. D. and Marcal, P. V., "A Numerical Thermo-Mechanical Model
for the Welding and Subsequent Loading of a Fabricated Structure,"
Computers and Structures, Vol. 3, No. 5, September 1973, pp. 1145-1174.
4. Muraki, T., Bryan, J. J., and Masubuchi, K., "Analysis of Thermal Stress
and Metal Movement During Welding," Trans. ASME, J. Engr. Materials and
Techn., Vol. 97, Series H, No. 1, January 1975, pp 81-91.
5. Paley, Z. and Hibbert, P. D., "Computation of Temperatures in Actual
Weld Designs," Welding Journal, Research Supplement, Vol. 54, No. 11,
November 1975.
6. Glickstein, S. S., Friedman, E., and Yeniscavich, W., "Investigation
of Alloy 600 Welding Parameters," Welding Journal, Research Supplement
Vol. 54, No. 4, April 1975, pp. 113s-122s.
7. Friedman, E. and Glickstein, S. S., "An Investigation of the Thermal
Response of Stationary Gas-Tungsten Arc Welds," Welding Journal,
Research Supplement, Vol. 55, No. 12, December 1976, pp. 408s-420s.
8. Friedman, E., "Thermomechanical Analysis of the Welding Process Using
the Finite Element Method," Trans. ASME, J. Pressure Vessel Tech.,
Vol. 97, Series J, No. 3, August 1975, pp. 206-213.
9. "Engineering Properties of Inconel Alloy 600," Technical Bulletin T-7,
International Nickel Co., Huntington, W. Va., 1964.
10. Pavelic, V., et. al., "Experimental and Computed Temperature Histories
in Gas Tungsten-Arc Welding of Thin Plates," Welding Journal, Research
Supplement, Vol. 48, No. 7, July 1969, pp. 295s-305s.
11. McAdams, W. H., Heat Transmission, Third Edition, McGraw Hill, New York,
1954.
12. Touloukian, Y. S. and DeWitt, D. P., "Thermophysical Properties of
Matter" Vol. 7, IFI/PLENUM, New York, 1970.
13. Glickstein, S. S., "Temperature Measurements in a Free Burning Arc,"
Welding Journal, Research Supplement, Vol. 55, No. 8, August 1976,
pp. 222s-229s.
14. Friedman, E., "Analysis of Weld Puddle Distortion and Its Effect On
Penetration," Welding Journal, Research Supplement, Vol. 57, No. 6,
June 1978, pp. 161s-116s.

15. Friedman, E., and Sattinger, S. S., "Temperatures and Distortions Induced by Omega Seal Closure Welding," ASME Paper No. 76-WA/PVP-20, December 1976.
16. Rosenthal, D. and Schmerber, R., "Thermal Study of Arc Welding," Welding Journal, Research Supplement, Vol. 17, No. 4, April 1938, pp. 2s-8s.
17. Glickstein, S. S., "Arc Modeling for Welding Analysis," WAPD-TM-1382, April 1978.

TABLE 1. SUMMARY OF WELDING CONDITIONS

Test Number	Speed, v (mm/s)***	Plate Thickness (mm)****	Current I (A)	V _m * (V)	V ₂ * (V)	V _e * (V)	V _a * (V)	I x V _a (W)	(I x V _a) _m ** (W)
254	2.067	6.35	138.5	9.85	0.90	0.66	8.30	1150	
255	2.067	6.35	138.0	9.90	0.90	0.66	8.35	1150	
256	2.067	6.35	138.5	9.90	0.90	0.66	8.35	1155	1150
257	2.067	6.35	70.5	8.25	0.45	0.15	7.65	540	
258	2.067	6.35	70.5	8.10	0.45	0.15	7.50	530	535
259	2.067	6.35	105.5	8.80	0.70	0.35	7.75	820	
260	2.067	6.35	105.5	9.00	0.70	0.35	7.95	840	830
261	4.133	6.35	140.0	10.10	0.90	0.66	8.55	1195	
262	4.133	6.35	139.5	9.95	0.90	0.66	8.40	1170	
263	4.133	6.35	139.0	10.10	0.90	0.66	8.45	1175	1180
264	4.133	6.35	106.5	9.00	0.70	0.35	7.95	845	
265	4.133	6.35	107.0	8.90	0.70	0.35	7.85	840	840
266	4.133	6.35	71	8.40	0.45	0.15	7.80	555	555
295	2.0	3.18	75	9.0	0.48	0.17	8.35	630	620
298	2.0	3.18	74	8.9	0.48	0.17	8.25	610	
296	2.0	3.18	100	9.0	0.64	0.30	8.1	810	800
299	2.0	3.18	99	8.9	0.64	0.30	8.0	790	
297	2.0	3.18	124	9.0	0.80	0.50	7.7	950	950
301	2.0	3.18	124	9.0	0.80	0.50	7.7	950	
300	2.0	3.18	149	9.0	0.95	0.80	7.25	1080	
302	2.0	3.18	150	8.8	0.95	0.80	7.05	1060	1075
315	2.0	3.18	150	9.0	0.95	0.80	7.25	1090	
303	2.0	1.59	49	8.9	0.32	0.07	8.5	420	
304	2.0	1.59	49	8.9	0.32	0.07	8.5	420	
305	2.0	1.59	49	8.9	0.32	0.07	8.5	420	425
306	2.0	1.59	50	8.9	0.32	0.07	8.5	430	
307	2.0	1.59	50	8.9	0.32	0.07	8.5	430	
312	2.0	1.59	51	8.9	0.32	0.07	8.5	430	
310	2.0	1.59	63	8.9	0.40	0.12	8.4	530	530
311	2.0	1.59	63	8.9	0.40	0.12	8.4	530	530
308	2.0	1.59	75	8.9	0.48	0.17	8.25	620	
309	2.0	1.59	75	8.9	0.48	0.17	8.25	620	620
313	2.0	1.59	75	8.9	0.48	0.17	8.25	620	
314	2.0	1.59	75	8.9	0.48	0.17	8.25	620	

*V_m = measured voltage; V₂ = voltage drop in line cable; V_e = voltage drop in electrode;

V_a = V_m - V₂ - V_e = net voltage drop in arc (6).

** = mean value

***2.0 mm/s = 4.72 ipm; 2.067 mm/s = 4.88 ipm; 4.133 mm/s = 9.76 ipm

****6.35 mm = 0.250 in; 3.18 mm = 0.125 in., 1.59 mm = 0.63.

TABLE 2. THERMAL RESPONSE OF TEST WELDS

Test Number	T ₁ peak (°C)	T ₂ peak (°C)	T ₃ peak (°C)	T ₄ peak (°C)	T ₇₀ peak (°C)	Top Width (mm)	Depth (mm)	Bottom Width (mm)
254	980	600	635	400	-----	7.6	1.5	-----
255	725	825	620	410	-----	7.3	1.6	-----
256	700	820	610	395	-----	7.3	1.6	-----
Mean	800	750	620	400	-----	7.4	1.6	-----
257	395	470	310	185	-----	3.3	0.6	-----
258	---	435	285	190	-----	3.2	0.6	-----
Mean	395	450	295	185	-----	3.2	0.6	-----
259	590	650	455	280	-----	5.3	1.1	-----
260	565	635	500	305	-----	5.0	1.2	-----
Mean	575	640	475	290	-----	5.1	1.1	-----
261	360	565	340	210	-----	5.7	1.3	-----
262	335	515	310	210	-----	5.7	1.2	-----
263	---	525	390	230	-----	5.7	1.2	-----
Mean	345	535	345	215	-----	5.7	1.2	-----
264	415	415	295	180	-----	4.3	1.0	-----
265	365	410	275	170	-----	4.2	1.0	-----
Mean	390	410	285	175	-----	4.2	1.0	-----
266	195	290	180	-----	-----	2.5	0.5	-----
295	710*	920*	660*	360*	220*	4.75	0.90	-----
298	610	1090	660	380	330	4.50	0.95	-----
Mean	610	1090	660	380	330	4.65	0.92	-----
296	840*	1240*	820*	430*	370*	6.45	1.45	-----
299	810	1240	870	460	400	6.20	1.35	-----
Mean	810	1240	870	460	400	6.32	1.40	-----
297	970	1250	970	560	480	7.20	2.10	-----
301	960	1290	990	560	470	7.60	2.35	-----
Mean	965	1270	980	560	475	7.40	2.22	-----
300	-----	-----	-----	-----	-----	8.15	-----	1.85
302	1010	1350	-----	560	500	7.95	2.70	-----
315	910*	1260*	1070	580	490	8.90	2.25	-----
Mean	1010	1350	1070	570	495	8.32	2.48	-----

TABLE 2. (CONT)

Test Number	T1 peak (°C)	T2 peak (°C)	T3 peak (°C)	T4 peak (°C)	T70 peak (°C)	Top Width (mm)	Depth (mm)	Bottom Width (mm)
303	----	----	----	----	----	3.35	1.10	----
304	----	----	----	----	----	3.75	----	1.70
305	----	----	----	----	----	3.50	----	1.70
306	860*	880*	980*	540*	390*	3.85	----	1.80
307	930	(1290)	880	450	360	3.85	----	----
312	900	(1270)	860	420	350	3.70	1.45	----
Mean	915	1280	870	435	355	----	----	----
310	950	(1360)	1000	490	400	5.20	----	4.50
311	1000	(1220)	980	420	410	5.05	----	4.35
Mean	975	1290	990	455	405	5.12	----	4.42
308	----	----	1100	570	440	6.00	----	4.50
309	920*	(1240)	1020	----	----	5.55	----	4.75
313	1070	----	1150	570	430	7.00	----	6.50
314	----	----	1100	610	470*	6.70	----	5.70
Mean	1070	(1240)	1090	585	435	6.30	----	5.70

() Tc in puddle; questionable data.

*Questionable data; not used for estimating mean.

TABLE 3. RESIDUAL DISTORTION OF 1.59 mm (1/16 in) THICK WELD PLATES
WELD SPEED = 2 mm/sec (4.72 ipm)

Position	Distortion* (mils)											
	I = 50A						I = 63A		I = 75A			
	#303	#304	#305	#306	#307	#312	#310	#311	#308	#309	#313	#314
1	0	0	0	0	0	0	0	0	0	0	0	0
2	85	115	92	100	97	105	130	130	150	150	145	130
3	220	227	220	226	230	255	300	293	343	330	325	345
4	140	145	143	150	155	165	203	180	225	200	200	225
5	0	0	13	40	27	25	46	20	50	10	25	25
6	-10	-5	-5	0	0	0	0	0	0	8	0	0
7	72	102	80	95	92	100	125	120	150	150	145	145
8	180	210	191	210	206	220	260	263	300	300	298	309
9	125	125	125	120	130	135	165	150	185	180	177	190
10	0	-10	4	8	0	10	10	0	10	0	10	5
11	-5	0	0	0	3	5	6	15	2	20	0	13
12	75	120	85	95	100	105	140	150	150	170	155	140
13	200	250	215	240	237	245	295	307	240	358	360	360
14	150	158	148	162	150	160	180	185	215	215	235	235
15	5	0	10	17	18	18	17	12	25	22	55	32

*Tabulated data is relative to position #1 (See Figure 4).

TABLE 4. RESIDUAL DISTORTION OF 3.18 mm (1/8 in) THICK WELD PLATES
WELD SPEED = 2 mm/s (4.72 ipm)

Position	Distortion* (mils)								
	I = 75A		I = 100A		I = 125A		I = 150A		
	#295	#298	#296	#299	#297	#301	#300	#302	#315
1	0	0	0	0	0	0	0	0	0
2	8	4	9	6	5	20	3	13	-2
3	16	17	24	20	13	44	6	30	-2
4	8	14	21	18	17	35	3	19	15
5	0	8	12	12	18	27	8	3	20
6	13	-1	0	-1	0	2	-5	17	3
7	13	0	5	3	3	15	1	25	-3
8	19	8	17	13	11	34	6	36	-3
9	11	7	12	11	12	28	3	21	11
10	5	0	0	2	5	15	-1	5	12
11	23	10	6	8	5	0	4	29	2
12	25	6	5	5	8	12	7	40	-5
13	27	9	15	10	12	26	8	52	-5
14	12	3	9	4	5	11	2	28	4
15	0	-3	0	-1	0	0	-3	2	1

*Tabulated data is relative to position #1. (See Figure 4).

TABLE 5. RESIDUAL DISTORTION OF 6.35 mm (1/4 in) THICK WELD PLATES
FOR VARYING CURRENTS (I) AND WELD SPEEDS (v)

Distortion* (mils)													
v = 2.067 mm/s (4.88 ipm)								v = 4.133 mm/s (9.76 ipm)					
Position	I = 70A		I = 105A		I = 139			I = 70A	I = 107A		I = 140A		
	#257	#258	#259	#260	#254	#255	#256		#265	#264	#265	#261	#262
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	3.5	3	6	4.5	1.5	3	3	4	6	3.5	4	4	2
3	4.5	4	7	5	1	3	2	6	7	5	4	5	3
4	3	3	5	3	0	3	1	5	6	3	2	4	2
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	3.5	3	4	6	5.5	6.5	7	2.5	5	4	6	7.5	5.5
7	10	10.5	15	15	13	14	14	9	16	12	15	16.5	13.5
8	12	12.5	18	16.5	13	16	15	11.5	18.5	14	17	19.5	16
9	11.5	12	16	16	14	16.5	14	10	17	13	17	18	16
10	9	9	19	12	14	17	12	5	12	10	14	14	13
11	11	0	0	0	0	0	0	0	0	0	0	0	0
12	2	3.5	4	2	1	0	1	3.5	7	3	3	4	3
13	3.5	4	5	4	0	0	1	5	10	5	4	7	5
14	3	4	2	4	-1	1	0	4	8.5	5	4	7	5
15	1	1	-3	2.5	-2.5	0	-4	-1	3.5	1	1	4	3

*Tabulated data is relative to position #1 (See Figure 4).

TABLE 6. SUMMARY OF MEASURED PLATE DISTORTION IN ALLOY-600 WELD TESTS

Plate Thickness (mm)	Weld Current (A)	Weld Speed (mm/s)	Residual Distortion	
			Transverse (mm)	Longitudinal (mm)
6.35	70-100	2.1	~0.1	~0.2
	140	4.0	~0.1	~0.2
3.18	125-150	2.0	0-0.25	~0.75
	75-100	2.0	---	~0.5
1.59	75	2.0	~1	~7
	50	2.0	0.25-0.5	~5

TABLE 7. CALCULATED INHERENT DISTORTION (δ) FOR TYPICAL VALUES OF
BEAD-ON-PLATE WELDING CONDITIONS STUDIED

Plate Thickness <u>h(mm)</u>	Weld Current <u>I(A)</u>	Weld Speed <u>v(cm/s)</u>	Inherent Shrinkage <u>X</u>	<u>δ(radians)</u>	<u>δ(mm)*</u>
6.35	100	0.4	310	0.01	0.25
3.18	100	0.2	1250	3×10^{-5}	7.5×10^{-4}
1.59	50	0.2	1760	4×10^{-7}	10^{-5}

*5 cm wide plate

Figure 1a. Experimental Arrangement for Positioning Weld Plates in Fixture

Figure 1b. Location of Thermocouple (TC) and Direct Current Displacement Transducers (DCDT) on Underside of Weld Sample (TC No. 1 on Top Surface)

Figure 1c. Positions of Displacement Transducers in Weld Fixture

Figure 2. Calibrated Voltage Output as a Function of Deflection for Direct Current Displacement Transducer (DCDT) No. 1

Figure 3. Typical Temperature and Distortion Transient Data from Thermocouple and Displacement Transducer Channels

Figure 4. Location of Residual Distortion Measurements, δ

Figure 5. Weldment Configuration

Figure 6. Typical Finite Element Mesh

Figure 7. Distortion of Thin Weld Plates

Figure 8. Typical Experimental Deflection Transients as Recorded at Displacement Transducer Positions Noted in Figure 1. (1 mil = 0.0254 mm)

Figure 9. Normal Total Emittance for Various Surface Conditions of Oxidized Stainless Steels as a Function of Temperature⁽¹²⁾

Figure 10. Measured and Calculated Temperatures of 1.59 mm Thick Alloy-600 Plate Initially at 1000°C Cooled in Air

Figure 11. Measured and Calculated Temperatures of 3.18 mm Thick Alloy-600 Plate Initially at 1000°C Cooled in Air.

Figure 12. Measured and Calculated Temperatures of 6.35 mm Thick Alloy-600 Plate Initially at 1000°C Cooled in Air

Figure 13. Calculated and Measured Temperature Transients at Thermocouple Positions TC1, TC2, TC3, and TC4 Noted in Figure 1

Figure 14. Calculated and Measured Peak Temperatures. Plate Thickness = 1.5 mm, Weld Speed = 2 mm/s, $T(70)$ = Temperature of all Thermocouples After 70 Sec, T_m = Melting Temperature

Figure 15. Calculated and Measured Peak Temperatures. Plate Thickness = 3.18 mm, Weld Speed = 2 mm/s, $T(70)$ = Temperature of all Thermocouples After 70 Sec, T_m = Melting Temperature

Figure 16. Calculated and Measured Peak Temperatures. Plate Thickness = 6.35 mm, Weld Speed = 4.133 mm/s

Figure 17. Calculated and Measured Peak Temperatures. Plate Thickness = 6.35 mm, Weld Speed = 2.067 mm/s

Figure 18. Calculated and Measured Weld Bead Dimensions.
Weld Speed = 2 mm/s, Plate Thickness = 1.59 mm

Figure 19. Calculated and Measured Weld Bead Dimensions.
Weld Speed = 2 mm/s, Plate Thickness = 3.18 mm

Figure 20. Calculated and Measured Weld Bead Dimensions.
Weld Speed = 2.067 mm/s, Plate Thickness = 6.35 mm

Figure 21., Calculated and Measured Weld Bead Dimensions.
Weld Speed = 4.133 mm/s, Plate Thickness = 6.35 mm

Figure 22. Effect of Arc Current and Plate Thickness h , on Heat Input Distribution Parameter $\bar{r}$. Weld Speed = 2 mm/s

2 SEC.

30 SEC.

60 SEC.

135 SEC.

Figure 23. Photographs of Argon Arc Incident on Cooled 6.35 mm Thick Alloy-600 Plate as a Function of Time After Arc Ignition. $I = 50A$

2 SEC.

30 SEC.

60 SEC.

90 SEC.

Figure 24. Photographs of Argon Arc Incident on Cooled 6.35 mm Thick Alloy-600 Plate as a Function of Time After Arc Ignition. $I = 100A$

Figure 25. Calculated "Inherent Angular Change" δ , for a Bead on Plate Weld as a Function of "Inherent Shrinkage Parameter" X

Figure 27. Effect of Weldment Thickness on Weld Bead Dimensions. Heat Input = 450W, Weld Speed = 2 mm/s, Heat Input Distribution Parameter $\bar{r} = 4.8$ mm

Figure 28. Effect of Weldment Thickness on Weld Bead Dimensions for Different Heat Input Parameters $\bar{r}$. Heat Input per Unit Thickness $(Q/h) = 142 \text{ kW/m}$. Weld Speed = 2 mm/s

Figure 29. Variation of Peak Temperatures with Weld Speed. Heat Input (Q/v) = 218 kJ/m

Figure 30. Variation of Weld Bead Dimensions with Weld Speed.
Heat Input (Q/v) = 218 kJ/m

Figure 31. Effect of Arc Current and Weld Speed on Distribution of Heat Input

U.S. GOVERNMENT PRINTING OFFICE: 1979-603-113/24