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HEAT SINK EFFECTS ON WELD BEAD - VPPA PROCESS

Prepared by: Paul O. Steranka, Jr.

Academic Rank: Assistant Professor

University and Department: Wichita State University
                                Department of
                                Mechanical Engineering

NASA/MSFC:
   Laboratory: Materials and Processes
   Division: Process Engineering
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MSFC Colleague: Arthur C. Nunes

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Paul O. Steranka, Jr.

Assistant Professor of Mechanical Engineering

Wichita State University

Wichita, Kansas

ABSTRACT

An investigation into the heat sink effects due to weldment irregularities and fixtures used in the variable polarity plasma arc (VPPA) process has been conducted. A basic two-dimensional model was created to represent the net heat sink effect of surplus material using Duhamel's theorem to superpose the effects of an infinite number of line heat sinks of variable strength. Parameters were identified that influence the importance of heat sink effects. A characteristic length, proportional to the thermal diffusivity of the weldment material divided by the weld torch travel rate, correlated with heat sinking observations. Four tests were performed on 2219-T87 aluminum plates to which blocks of excess material were mounted in order to demonstrate heat sink effects. Although the basic model overpredicted these effects, it correctly indicated the trends shown in the experimental study and is judged worth further refinement.

INTRODUCTION

The purpose of this study was to identify the important parameters that determine the "heat sink" effects due to fixtures used in the variable polarity plasma arc (VPPA) welding process and to develop a model for the prediction of these effects. This study is one contribution to an ongoing project to develop a comprehensive weld model to be used for automatic control of the welding process.

Arc welding is a complex process that involves such diverse fields as arc physics, metallurgy, heat transfer, and fluid mechanics. Understanding of the interactions among various constituent processes is necessary for the accurate modeling required for the automatic control of welding. The complexity of the task of developing automatic control of welding processes is indicated in a report prepared by the Committee on Welding Controls of the National Materials Advisory Board of the National Research Council [1]. In this report discussion of various types of welding is provided and gas-tungsten-arc (GTA) welding is identified as "probably the most amenable to control of the various arc welding processes." In assessing the state of the art in control of the GTA process, the Committee on Welding Controls identifies 14 "main inputs (controllable at time and point of welding)" and 47 "disturbing inputs (not at present controllable and subject to variation at time and point of welding)." Five of the 47 "disturbing inputs" are tied to the fixturing and tooling used in the welding process. A similar list of inputs could be made for the VPPA process that would include the thermal effects of fixtures studied in the current project.

Plasma arc welding is classified by the International Institute of Welding as a "high power density" welding process along with such processes as electron beam welding and laser welding [2]. In plasma arc welding, as in GTA welding, an arc is established through an inert gas (typically argon) between a non-consumable tungsten electrode and the workpiece. In the plasma arc process the pressure created by the impinging jet of gas together creates a depression in the weld pool and in some cases the jet may completely penetrate the the object being welded. Under these circumstances metal being melted in advance of the moving welding torch moves around the "keyhole" formed by the beam and solidifies behind the torch. VPPA welding is a form of plasma arc welding frequently (although not always) performed in this "keyhole mode" in

which the polarity of the electrode relative to the workpiece is periodically reversed from direct current electrode negative (DCEN) to direct current electrode positive (DCEP). This periodic reversal of polarity (DCEP for approximately 4 milliseconds out of a 23 millisecond cycle) provides a "cleansing" of oxide films that readily form on the surface of a metal. This process has been described in the literature [3,4] and has been used successfully to weld aluminum in such applications as the welding of the Space Shuttle External Tank.

In VPPA welding, as in any welding process, heat transfer from the weld zone to the surroundings, including fixtures used in the process, plays an important role in determining the characteristics of the weld. The fixtures used in welding vary greatly in form, mass, placement in relation to the weld zone, and the like. In perhaps the simplest case, a fixture may consist of a simple metal frame to which a workpiece is connected using C-clamps as shown in Figure 1. In this case the fixture contact points may be far from the weld zone. In other cases, fixtures may consist of a series of "fingers" or solid jaws that may clamp down on the workpiece close to the weld zone over the whole length of the weld as shown in Figure 2. In the case of the welding of an object such as the Space Shuttle External Tank, a fixture may have to be a major structure in itself as seen in Figure 3. Although it is not possible to simply characterize all the fixtures used in practice, it is possible to identify certain characteristics of fixtures that may lead to significant heat absorption during a welding process.

Different authors have presented results of calculations or measurements of the temperature distributions created in welding. In the 1940's, Rosenthal [5] published analytical solutions for temperature distributions created by moving sources of heat such as those used in welding. A number of authors, including Christensen, Davies, and Gjermundsen [6] and Nunes [7], have used the Rosenthal solutions as starting points for their analyses. Other investigators, for example Zacharia, Eraslan, and Aidun [8] and Okada, Kasugai and Hiraoka [9], have proposed numerical solutions for temperatures in and around the weld pool. In the references cited, the attention of the authors was generally directed to the phenomena taking place in the weld pool which is obviously of importance. As a consequence, the assumptions made about conditions outside the weld zone were kept simple, for example, negligible heat transfer from the surface of the workpiece to the surroundings and constant temperature at large distances from weld or a well-behaved convective boundary condition from the surface to a constant temperature.

It appears that no general studies to assess the importance
of heat absorption due to fixtures have been performed to
date. The current project is an attempt to provide a first
step in that direction.
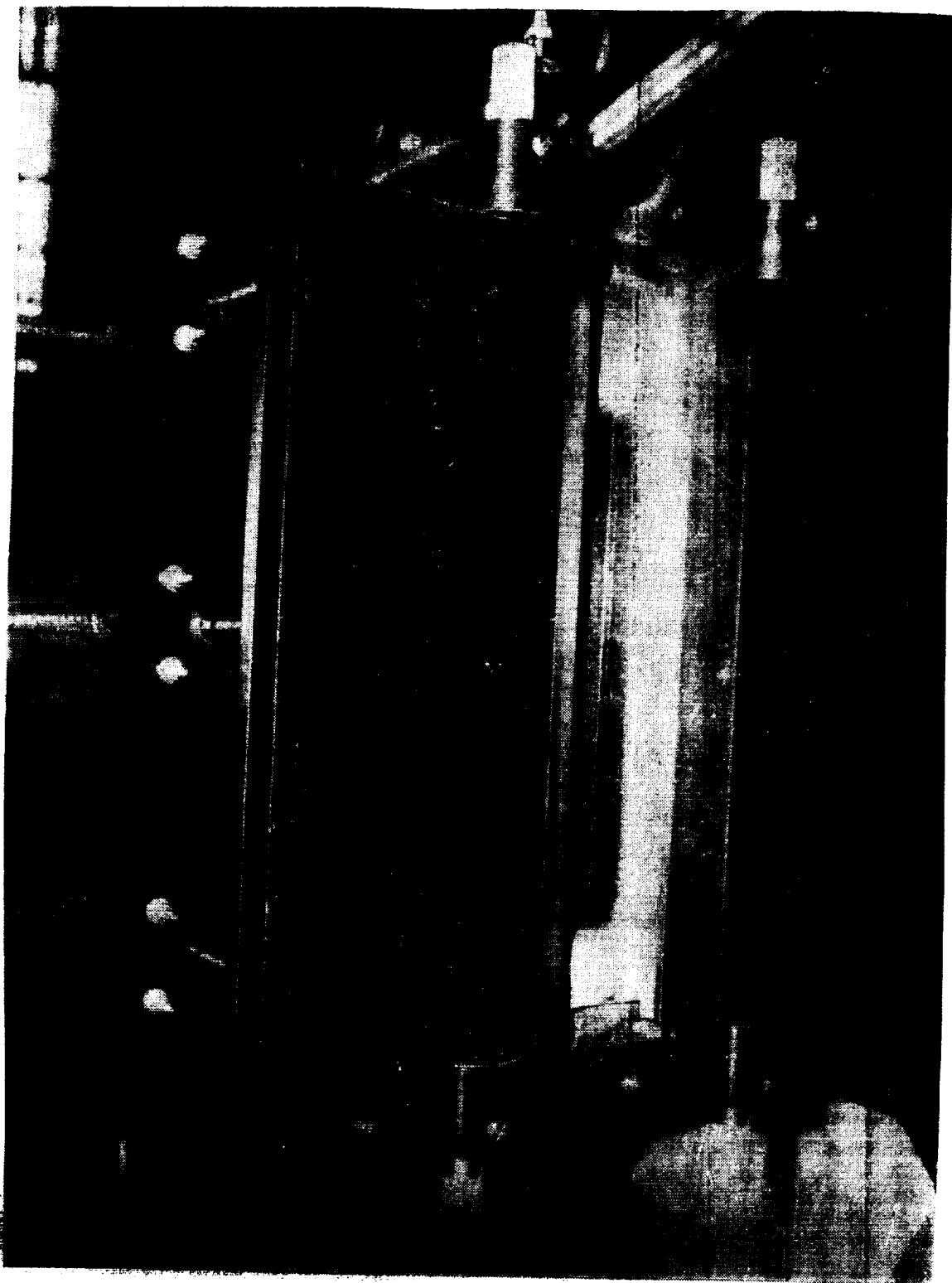

Figure 1. Simple welding fixture.

Figure 2. Welding fixture with contact along length of weld.
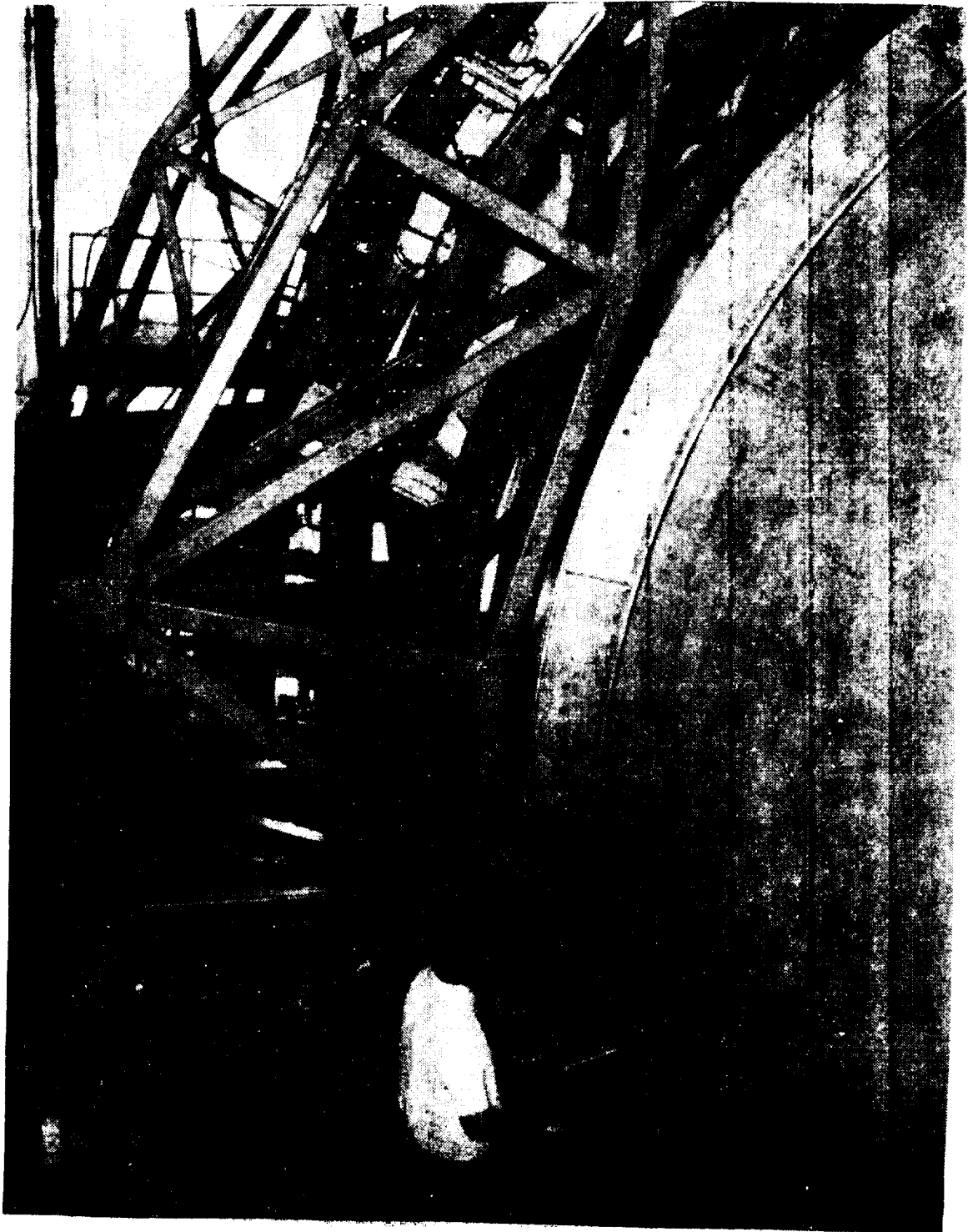
Figure 3. Fixture for welding of Space Shuttle
External Tank.

OBJECTIVES

The primary objectives of this project were to investigate the importance of the effects of heat transfer to fixtures or to irregularities in the structure of the weldment itself on the VPPA welding process and to develop a basic model to estimate these effects. Experimental demonstration of the "heat sinking" effect due to material in contact with a plate being welded was also planned in order to evaluate the model.

Progress was made toward identifying the circumstances under which fixtures used in the welding of plates play a significant role in the heat transfer of the process. A basic model was developed to estimate the magnitude of these "heat sink" effects. The experimental demonstration indicated that although the current model correctly predicts the trends in the importance of heat sinking with variation of heat sink parameters, it overpredicts the magnitude of these effects.

MODEL DEVELOPMENT

The present study involved identification of the parameters that determine the importance of the absorption of heat in surplus material near the weld zone and development of a simple two-dimensional model to indicate the magnitude of the heat sinking effect under different conditions. In the development of such an model, a method for computing the temperature field created by the welding process is required. For a fixture to have a thermal effect on the weld zone, the temperature distribution created by the welding process itself must first reach the fixture location. Then through approximation of the interaction of the temperature field with the fixture material, the heat sink effect of the fixture may be estimated.

For the present model a simple expression that reflects the important characteristics of the temperature distribution created by the welding process was sought. Rosenthal's closed form solution [5] for the two-dimensional temperature distribution created by a moving line source was selected for this purpose. This solution is based on the assumptions of constant thermal properties, negligible natural convection losses from the front and back of the plate, even heat input per unit length along the line source through the plate, and a fixed temperature at large distances from the source. The resulting steady temperature distribution for a moving coordinate system attached to the source is given by

$$T_R(x,y) \; - \; T_0 \; = \; \frac{Q'}{2\pi k} \; e^{-(Vx/2\alpha)} \; K_0(Vr/2\alpha)$$

where the motion of the source is parallel to the x-direction with velocity V; Q' is the source strength per unit length; k and α are the thermal conductivity and thermal diffusivity of the plate, respectively; K_0 is the modified Bessel function of the second kind of order 0; and $r = (x^2 + y^2)^{1/2}$.

If the Rosenthal solution is examined in detail, it is seen that the exponential factor accounts for the "skewing" of the temperature distribution to create steep temperature gradients ahead of the source (when $x > 0$) compared to the shallow gradients behind the source. The Bessel function factor is symmetric about the source with a singularity at the origin and its values drop off rapidly with increasing values of its

argument. The product of these factors generates a typical form for contours of constant temperature about the source that is shown schematically in Figure 4. In both factors the characteristic length L = 2α/V appears. It is interesting to note the range of values that L may have for different materials. Representative values of L for 2219-T87 aluminum, type 304 stainless steel, and Inconel 718 for a torch travel speed of 8 inches/min. (20.3 cm/min) are shown in Table 1. The values vary greatly due to the different values of thermal diffusivity of these materials. The implication of these values is that for a given disturbance (such as the heat sink effect due to contact with a fixture) to have a similar effect on the welding of two different materials, the fixture would have to be located at different distances from the weld zone. For example, to have a similar effect on the welding of an aluminum plate as on a stainless steel plate, a fixture would have to be placed closer to the weld zone by a factor of 11 on the stainless steel plate. For an aluminum plate and an Inconel 718 plate the characteristic lengths differ by a factor of more than 80! The values of this characteristic length thus have great importance in estimation of the significance of potential heat sink effects.   A fixture located at a distance of several of these charcteristic lengths should have no significant effect on the heat transfer in the vicinity of the welding torch.
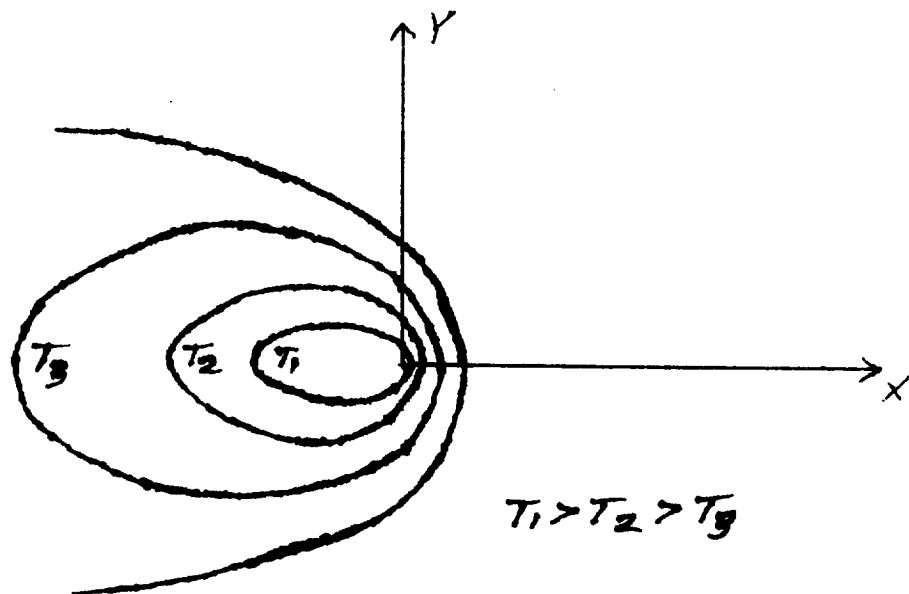

Figure 4.   Typical form of constant temperature contours from the Rosenthal line source solution.

Table 1. Typical values of characteristic length L for different materials for a torch travel rate of 8 in./min (20.3 cm/min).

MATERIAL	CHARACTERISTIC LENGTH L
2219-T87 Aluminum	1.2 in (3.0 cm)
Type 304 Stainless Steel	0.11 in (0.28 cm)
Inconel 718	0.014 in (0.036 cm)

After selection of the Rosenthal model to represent the temperature distribution in a plate created by the welding process, a method was developed for estimation of the heat sinking effect due to interaction of this temperature field with a mass in contact with the plate at a fixed location. From the Rosenthal moving line source solution it is possible to generate the temperature history at a point on the plate. If a small mass on the plate were to interact with the moving temperature distribution, a simple estimate of the heat it would draw from the plate would be equal to the quantity of heat required for the temperature of the small mass to attain the temperatures prescribed for its location by the Rosenthal solution. This premise forms the basis of the model created for estimation of the heat sink effect.

With the frame of reference for the calculations moving with the welding torch fixed at the origin, as in the Rosenthal solution, the heat sink effect caused by a mass fixed to the plate is equivalent to that of a moving heat sink of variable strength. Carslaw and Jaeger [10] provide the solution for the two-dimensional temperature distribution created by an instantaneous line source of strength per unit length Q' occurring at time τ located at (x_0, y_0) as

$$T(x,y,t) - T_0 = \frac{Q'}{4\pi\alpha(t-\tau)} \exp[-\{(x-x_0)^2 + (y-y_0)^2\}/\{4\alpha(t-\tau)\}]$$

For a moving source (or sink) of variable strength, Duhamel's theorem may be used to superpose the effects of an infinite number of instantaneous heat sources to determine an equivalent effect at a desired time and location. In the current model the instantaneous strength S of the heat sink at time τ is given by

$$S(\tau) = -\frac{mC_p}{d}(dT_R/d\tau)^{\cdot}{}_{x',y',\tau}$$

where x' and y' are the instantaeous coordinates of the heat sink, m and C_p are the mass and specific heat of the sink material, d is the thickness of the plate, and $dT_R/d\tau$ is the rate of change of the temperature from the Rosenthal solution at the location of the sink. Substitution of this expression into the Carslaw and Jaeger solution for an instantaneous source and applying Duhamel's theorem yields the following expression for determining the effect on the temperature at a point (x,y) at time t due to a sum of instantaneous sources occurring between time t_0 and time t:

$$T - T_0 = \int_{t_0}^{t} \frac{S(\tau)}{4\pi k(t-\tau)} \exp[-\{(x-x')^2+(y-y')^2\}/\{4\alpha(t-\tau)\}] \, d\tau$$

Numerical integration of this expression is performed by the computer program HTSINK.BAS described in the Appendix in order to determine the approximate maximum temperature depression at the weld zone due to the heat sink effect of a mass in contact with a plate being welded. Once this temperature depression is identified, the program goes on to shift the temperature distribution from the Rosenthal solution by the amount of the depression and to estimate the reduced weld bead width based on the melting isotherm shift for comparison with the bead width without the heat sink effect.

EXPERIMENTAL DEMONSTRATION OF HEAT SINK EFFECT

As part of the project it was desired to demonstrate heat sink effects in the welding of plates and correlate the results with the predictions of the computer model. To set up the first experiment, the computer model was used to estimate the effects of placing small blocks of aluminum near the weld zone prior to performing a bead-on-plate weld. A 1/4-inch 2219-T87 plate was selected for the test and 12 aluminum blocks measuring 2 in. X 1 in. X 0.5 in. (5.1 cm X 2.5 cm X 1.3 cm) were bolted in sets of four at distances of 1 in. (2.5 cm), 1.5 in. (3.8 cm), and 2 in. (5.1 cm) from the weld centerline on the front and back of the plate as shown in Figure 5. The computer model predicted a reduction of 22 % near the closest blocks, 10 % for the intermediate blocks, and less than 5 % for those furthest from the weld zone. The weld was performed using weld parameter settings of arc current: 155 amps, arc voltage: 28 volts, and torch travel rate: 11 in./min (28 cm/min). As may be observed in the photograph of Figure 6, no measurable effect occurred due to any of the blocks. Thus, the model had overpredicted the heat sinking effect.
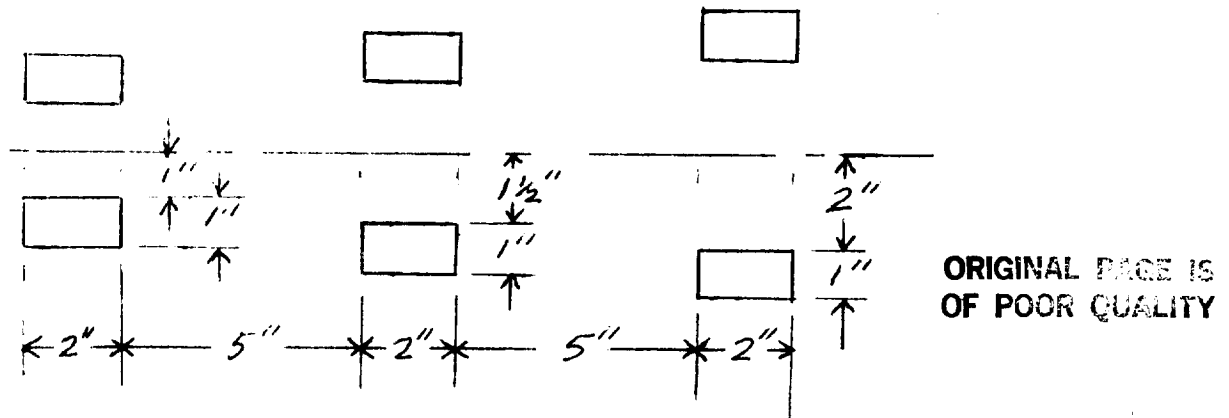
Figure 5. Heat sink block locations on plate 1.

Figure 6. Weld bead on plate 1 near heat sink blocks.

In order to increase the heat sink effect, the model indicates that the torch velocity or the distance from the weld zone could be decreased or the mass of the sink material increased. Due to clearance requirements for the VPPA torch, it was not possible to place blocks closer to the weld zone on the front of the plate. Since this limitation did not exist on the back of the plate, it was decided to mount larger blocks on the back of the plate closer to the weld zone. For this second experiment four 4 in. X 2 in. X 1 in. (10.2 cm X 5.1 cm X 2.5 cm) were bolted to the back of a 1/4-inch aluminum plate. Two of the blocks were placed 0.75 in. (1.9 cm) on either side of the weld centerline and the other two were 1.25 in. (3.2 cm) from the centerline as shown in Figure 7. The weld parameters used were the same as those for the first plate. In this case the model predicted reductions of 27 % and 13 % for the two sets of blocks. Once again, however, no noticeable reduction occurred during the experiment.
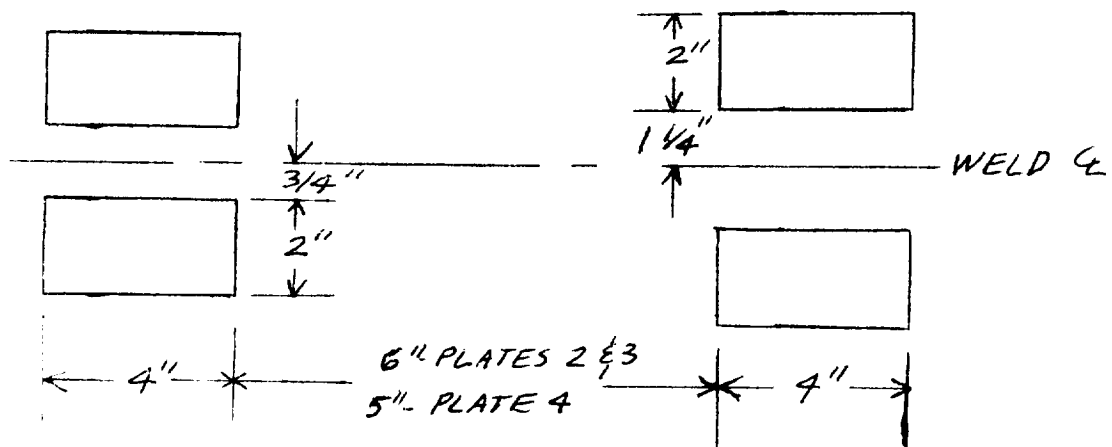

Figure 7. Heat sink block locations of plates 2,3. and 4.

A third experiment was conducted using the same blocks and spacing relative to the weld centerline as in the second experiment, but using a 1/2-inch 2219-T87 aluminum plate. For this weld the welding parameters were changed to arc current: 218 amps, arc voltage: 29.6 volts, and torch travel rate: 5.5 in./min (14 cm/min). Thus, the third factor for increasing the heat sink effect indicated by the model, torch velocity decrease, was added in this experiment. For these conditions the model predicted reductions of 40 % and 23 % for the two sets of blocks. On the back of the plate (where the blocks were mounted) maximum reductions of 18 % and 6 % were observed in the width of the root of the weld. The crown of the weld, on the other hand, showed no evidence of the heat sinking effect.

One factor that is suspected to play a significant role in determining heat sinking effects is contact resistance. In order to obtain an idea of the importance of contact resistance, a last experiment was conducted using the same blocks with the same spacing from the weld zone as in the second and third plates. For this fourth plate, the thickness of 1/2-inch was used again and the schedule of weld parameters was changed slightly to arc current: 215 amps, arc voltage: 28.5 volts, and torch travel rate: 5.5 in./min (14 cm/min). This time, however, the four blocks were coated with heat-conducting grease prior to being bolted to the plate. Under these circumstances the reductions in the width of the weld root were determined to be 13 % and 8 %. These reductions may be observed in Figure 8. It therefore appears that the addition of the heat conducting grease created no significant increase in the heat sink effect. In fact, in the experiment conducted the reduction in weld bead width due to the closest blocks actually decreased.

In addition to comparison with predictions from the current model, the crown and root weld bead widths from the experimental study were used as inputs to the existing MSFC Weld Model [7] in order to estimate the power absorbed by the heat sink blocks. According to the model, for plate 3, the root bead reductions of 18 % and 6 % correspond to absorption of 2.7 % and 1.0 % of the power transmitted to the plate, respectively. For plate 4, the 13 % and 8 % reductions correspond to absorption of 1.6 % and 1.1 % of the transmitted power. It is interesting to note that it appears that a power increase on the order of a few per cent would be sufficient to compensate for the heat sink effect of the blocks used in the experiment.
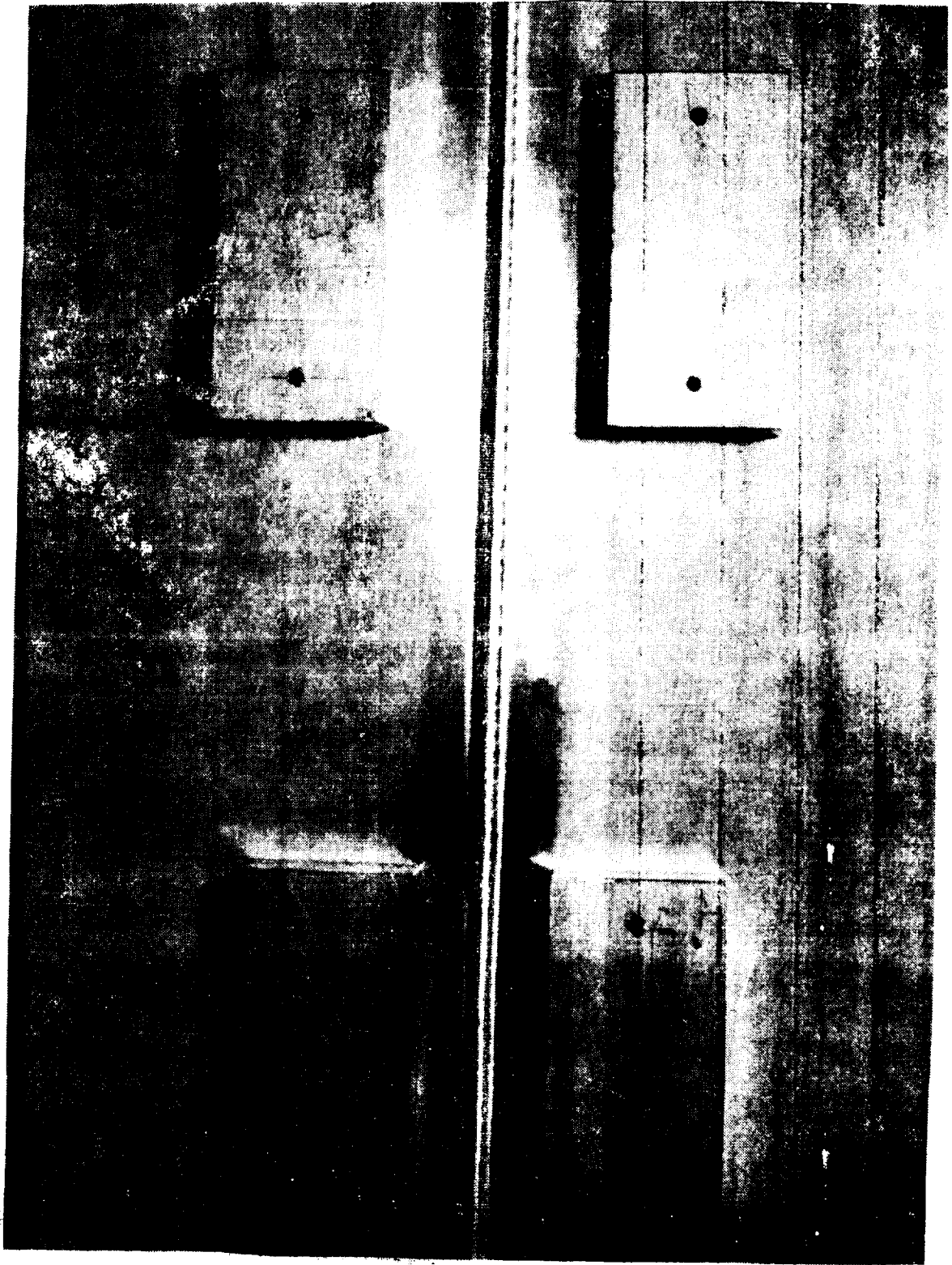
Figure 8.   View of weld bead on plate 4.

CONCLUSIONS AND RECOMMENDATIONS

The objectives of this project were to identify parameters important to the heat sink effects due to weldment irregularities and to fixtures used in the VPPA welding process, to develop a basic model for prediction of these effects, and to demonstrate these effects in the laboratory. All these objectives were satisfied.

Two important heat sink parameters that were identified were the distance from the weld zone and the thermal capacity of the sink material. The distance of the fixture from the weld zone may be expressed in terms of a characteristic length equal to the $2\alpha/V$, where α is the thermal diffusivity of the plate being welded and V is the torch travel velocity. Any sink more than a few of these characteristic lengths from the weld zone has little effect on the weld. The thermal capacity (mass times specific heat) of the heat sink material in contact with the workpiece also plays an obvious role in determining the amount of energy that may be absorbed in the heat sink.

A simple two-dimensional model was developed for predicting the heat sink effect of a small mass in contact with a plate being welded. Although the model consistently overpredicted the magnitude of the heat sink effects, it appears to reflect the trends observed in the experimental demonstration. The current version of the model lacks the accuracy that would be required for its use for control of the welding process, but it presents a beginning susceptible to considerable improvement.

Continued work is recommended in the study of heat sink effects. A more sophisticated model appears to be necessary to accurately predict the importance of these effects in different situations. In particular, a model that would represent the three-dimensional features of heat sink phenomena would provide greater flexibility to analyze configurations found in practical welding applications. Another area to be examined in the model development is the ability to handle different boundary conditions. Generally, studies of welding heat transfer effects to date have been based on simple boundary conditions, such as constant temperature at large distances from the weld or well behaved convective heat transfer over the entire weldment outside the weld zone itself. More complex conditions exist in any

practical situation and examination is needed of the effects of these conditions. One phenomenon that requires further work is contact resistance. Although the experiment conducted during the current project indicated contact resistance was not important in the case considered, further study is needed to assess the importance of this factor under different circumstances.

Finally, it should be noted that the importance of the study of heat sink effects is not confined to the VPPA process. Similar problems are present in other welding processes, in the heat treatment of metals, in dealing with hot spots in engines, and in many other processes. One interesting application is that of welding in space where both the heat transfer to the weldment from the welding apparatus and the heat transfer from the weldment to the surroundings would differ significantly from the processes that occur on earth. Another difficulty related to heat sink effects that is encountered in practice involves the welding of objects that have significantly different thermal masses such as joining a thin sheet of metal to a large block of metal. The situations cited are only a few of instances where heat sink effects play an important role. Further understanding of these effects will thus be of benefit in many applications.

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APPENDIX

This appendix contains a description and a listing of the
computer program HTSINK.BAS that was created to estimate the
effects of heat sinking due to surplus material, such as a
welding fixture, in contact with a plate to be welded.
HTSINK.BAS is an interactive program and begins with input of
parameters concerning the weld: plate material, plate
thickness, arc current, arc voltage, weld energy transfer
efficiency, and torch travel speed. Then the mass, specific
heat, and initial position of the sink with respect to the
torch are entered. Finally, the ambient temperature and the
total length of time to be analyzed are supplied.

With the information about the weld and heat sink supplied by
the user, the program calculations begin. The undisturbed (by
the heat sink) weld bead width is first determined. The width
is determined by identification of the point where the
distance from the weld centerline to the melt isotherm (based
on the Rosenthal temperature solution) is greatest. This
point is determined by applying the dichotomous search
strategy to the region between the torch position and the
puddle length along the weld axis. (Note: The Newton-Raphson
technique is employed for solution of the nonlinear equations
involved in the puddle length and width calculations.) With
the bead width determined, the program proceeds to analyze the
heat sink effects. The program numerically integrates the
expression for net heat sink effect for various lengths of
time and identifies the maximum sink effect and the position
of the sink at the time it occurs. Finally this heat sink
effect is superimposed on the Rosenthal temperature solution
and a new bead width is determined and compared with the
undisturbed bead width.

Listing of HTSINK.BAS

```
110 CLEAR
112 DIM TE(40)
115 PRINT "SELECT PLATE MATERIAL"
116 PRINT " "
120 PRINT "1 = 2219 ALUMINUM"
121 PRINT "2 = 304 STAINLESS STEEL"
122 PRINT "3 = INCONEL 718"
123 PRINT "4 = OTHER MATERIAL WITH USER SUPPLIED PROPERTIES"
124 PRINT " "
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```
130 INPUT "SELECTION"; A1
131 IF A1 = 1 THEN GOSUB 2100
132 IF A1 = 2 THEN GOSUB 2200
133 IF A1 = 3 THEN GOSUB 2300
134 IF A1 < 1 OR A1 > 3 THEN GOSUB 3000
140 INPUT "PLATE THICKNESS (IN.) "; TH
145 TH = TH/12
150 REM ***  INPUT WELDING PARAMETERS  ***
151 INPUT "WELDING CURRENT (AMPS)"; IO
152 INPUT "WELDING VOLTAGE (VOLTS)"; VO
153 INPUT "WELDING EFFICIENCY (%)"; EF
155 P=3.412*VO*IO*EF/100
157 INPUT "TORCH VELOCITY (IN/MIN)"; V
158 V=V/720
160 REM ** SINK CHARACTERISTICS **
163 PRINT " "
164 PRINT "SINK CHARACTERISTICS"
166 INPUT "SINK MASS (LB)";M
168 INPUT "SINK SPECIFIC HEAT (BTU/LB-F)"; CP
169 PRINT " "
170 PRINT "INITIAL POSITION OF SINK (IN) RELATIVE TO TORCH"
171  PRINT  "(TORCH  MOTION  IN  X-DIRECTION;  Y-DIRECTION
PERPENDICULAR"
172 PRINT " TO WELD PATH)"
173 PRINT " "
175 INPUT "X0,Y0";X0,Y0
176 X0=X0/12
177 Y0=Y0/12
180 REM ** TORCH AT ORIGIN **
181 X=0
182 Y=0
189 PRINT " "
190 INPUT "AMBIENT TEMPERATURE (F) ";TR
191 PRINT " "
193 PRINT "** DETERMINING WELD WIDTH **"
194 REM ** FIND STEADY WELD BEAD HALF WIDTH **
195 GOSUB 6000
196 BO=BW*(2*A/V)
197 PRINT " "
198 PRINT "INITIAL WELD BEAD WIDTH: "; BO*24; " INCHES"
199 PRINT " "
200 INPUT "LENGTH OF PERIOD TO BE STUDIED (SEC)";TX
201 REM ** SET UP PARAMETERS AND BEGIN INTEGRATION **
202 PRINT " "
203 PRINT "** NUMERICAL INTEGRATION BEGUN **"
204 T0=0
206 JJ=INT((TX-T0)/10)
208 FOR J=1 TO JJ
210 TF = 10*J
212 N=4*INT(TF/(2*A/V^2))+4
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```
214 D = (TF-T0)/N
216 L=0
218 R=0
220 FOR I = 0 TO N
230 T1 = T0 + I*D
240 IF I = N THEN F = 0
250 IF I = N THEN GOTO 270
260 GOSUB 1000
270 Z = L/2 - INT(L/2)
280 IF Z>0 AND L<N THEN LET T=4*F
290 IF Z=0 AND L<N-1 THEN LET T=2*F
300 IF L=0 OR L=N THEN LET T=F
310 L=L+1
320 R=R+T
330 NEXT I
340 Q= D*R/3
350 TE(J) = - 45.5945*P*Q*M*CP/(K*TH)^2
:REM CONST=3600/(8*PI)^2
355 REM PRINT "TIME = "; TF; "   TEMP. DEPRESSION = "; TE(J)
360 IF J=1 THEN GOTO 380
365 IF TE(J)>TE(J-1) THEN GOTO 400
380 NEXT J
400 TD=TE(J-1)
410 TI=TF-D
420 PRINT " "
430 PRINT "MAXIMUM TEMPERATURE DEPRESSION AT ORIGIN IS: "; TD
440 PRINT "AND OCCURS WHEN TORCH IS "; 12*(V*(TI-T0)-X0);
" INCHES"
450 PRINT "PAST SINK"
460 TR=TR+TD
470 REM ** FIND NEW WELD HALF WIDTH **
480 GOSUB 6000
490 BN=BW*(2*A/V)
500 PRINT "REDUCED WELD BEAD WIDTH: "; BN*24; " INCHES"
510 PRINT " "
520 PRINT "REDUCTION OF "; 100*(BO-BN)/BO; " %"
530 STOP

1000 REM SUBROUTINE FOR INTEGRAND
1010 X1=X0-V*(T1-T0)
1020 X2= X-X1
1030 Y2=Y-Y0
1035 FOR J4 = 1 TO 2
1040 BA=V*SQR((X1-(-1)^J4*V*D/2)^2+Y0^2)/(2*A)
1050 EX = (X2^2+Y2^2)/(4*A*(TF-T1)) +
(X1-(-1)^J4*V*D/2)*V/(2*A)
1055 IF (-EX-BA)<-80 THEN F=0 :GOTO 1120
1056 IF (-EX-BA)>-80 AND (BA>80) THEN FL=1
1060 GOSUB 1500
1065 IF FL=1 THEN F=K0*EXP(-EX-BA)/(TF-T1) : GOTO 1075
```

```
1070 F = K0 * EXP (-EX) / (TF-T1)
1075 FL=0
1080 IF J4=1 THEN LET FO=F
1090 IF J4=2 THEN LET FP=F
1100 NEXT J4
1110 F=(FP-FO)/D
1120 RETURN

1500 REM *** MODIFIED BESSEL FUNCTION, SECOND KIND OF ORDER
0 ***
1510 REM *** POLYNOMIAL APPROXIMATION ***
1520 IF BA<> 0 THEN 1550
1530 K0=100000!
1540 RETURN
1550 IF BA > 2 THEN 1650
1560 GOSUB 1700
1570 LET G2 = BA*BA/4
1580 LET K0 =((.0000074*G2+.0001075)*G2 +2.62698E-03)*G2
1590 LET K0 = ((K0+.0348859)*G2+.2306976)*G2
1600 LET K0 = ((K0+.4227842)*G2-.5772157)-.5*LOG(G2)*I0
1610 GOTO 1690
1650 LET G2 = 2/BA
1660 LET K0=((5.3208E-04*G2-.0025154)*G2 +5.87872E-03)*G2
1670 LET K0=((K0-1.062446E-02)*G2 + 2.189568E-02)*G2
1675 IF FL=1 THEN LET
K0=((K0-7.832358E-02)*G2+1.253314)/SQR(BA)
1676 IF FL=1 GOTO 1690
1680 LET K0=((K0-7.832358E-02)*G2+1.253314)/SQR(BA)/EXP(BA)
1690 RETURN

1700 REM *** MODIFIED BESSEL FUNCTION, FIRST KIND OF ORDER 0
***
1710 REM *** POLYNOMIAL APPROXIMATION ***
1720 IF BA>3.75 THEN 1780
1730 LET G1 = BA*BA
1740 LET I0=((5.923979E-10*G1+6.56017E-08)*G1+6.80123E-06)*G1
1750 LET I0=((I0+4.3394E-04)*G1+.0156252)*G1
1760 LET I0=(I0+.25)*G1+1
1770 GOTO 1820
1780 LET I0=((153.445/BA-171.822)/BA+73.2919)/BA
1790 LET I0=((I0-15.2595)/BA+1.81198)/BA
1800 LET I0=((I0-.0830909)/BA+.0316855)/BA
1810 LET I0=((I0+.0498222)/BA+.3989423)*EXP(BA)/SQR(BA)
1820 RETURN

2000 REM PROPERTY VALUE SUBROUTINES
2100 REM 2219 ALUMINUM PROPERTIES
2110 REM THERMAL DIFFUSIVITY IN FT^2/S AND
2111 REM CONDUCTIVITY IN BTU/HR/FT/F
2120 MT$="2219 ALUMINUM"
```

```
2130 A=.000503
2140 K=72
2150 TM=1190
2160 RETURN
2200 REM 304 STAINLESS STEEL PROPERTIES
2210 REM THERMAL DIFFUSIVITY IN FT^2/S AND
2211 REM CONDUCTIVITY IN BTU/HR/FT/F
2220 MT$="304 STAINLESS STEEL"
2230 A=.0000524
2240 K=14
2250 TM=2800
2260 RETURN
2300 REM INCONEL 718 PROPERTIES
2310 REM THERMAL DIFFUSIVITY IN FT^2/S AND
2311 REM CONDUCTIVITY IN BTU/HR/FT/F
2320 MT$="INCONEL 718"
2330 A=.0000063
2340 K=12
2350 TM=2437
2360 RETURN
3000 REM USER SUPPLIED MATERIAL PROPERTIES
3010 INPUT "MATERIAL DESIGNATION"; MT$
3020 INPUT "THERMAL DIFFUSIVITY IN FT^2/S"; A
3030 INPUT "THERMAL CONDUCTIVITY IN BTU/HR/FT/F"; K
3040 RETURN

4100 REM *** MODIFIED BESSEL FUNCTION, FIRST KIND OF ORDER 1
***
4110 REM *** POLYNOMIAL APPROXIMATION ***
4120 IF BA>3.75 THEN 4180
4130 LET G1 = (BA/3.75)^2
4140 LET I1=((3.2411E-04*G1+3.01532E-03)*G1+2.658733E-02)*G1
4150 LET I1=((I1+.15084934#)*G1+.51498869#)*G1
4160 LET I1=((I1+.87890594#)*G1+.5)*BA
4170 GOTO 4230
4180 LET G1=BA/3.75
4190 LET
I1=((-4.20059E-03/G1+1.787654E-02)/G1-2.895312E-02)/G1
4200 LET
I1=(((I1+2.282967E-02)/G1-1.031555E-02)/G1+1.63801E-03)/G1
4210 LET I1=(I1-3.62018E-03/G1-3.988024E-02)/G1+.39894228#
4220 LET I1=I1*EXP(BA)/SQR(BA)
4230 RETURN

5100 REM *** MODIFIED BESSEL FUNCTION, SECOND KIND OF ORDER
1 ***
5110 REM *** POLYNOMIAL APPROXIMATION ***
5120 IF BA<> 0 THEN 5150
5130 K1=100000!
5140 RETURN
```

```
5150 IF BA > 2 THEN 5220
5160 GOSUB 4100
5170 LET G2 = BA*BA/4
5180 LET K1 =((-4.686E-05*G2-1.10404E-03)*G2-1.919402E-02)*G2
5190 LET K1 = ((K1-.18156897#)*G2-.67278579#)*G2
5200 LET K1 = ((K1+.15443144#)*G2+1)/BA+LOG(BA/2)*I1
5210 GOTO 5260
5220 LET G2 = 2/BA
5230 LET K1=((-6.8245E-04*G2+3.25614E-03)*G2-7.80353E-03)*G2
5240 LET K1=((K1+1.504268E-02)*G2-.0365562)*G2
5250 LET K1=((K1+.23498619#)*G2+1.25331414#)/SQR(BA)/EXP(BA)
5260 RETURN

6000 REM *** SUBROUTINE FOR FINDING WELD BEAD WIDTH ***
6005 REM *** BASED ON DICHOTOMOUS SEARCH STRATEGY ***
6010 C1=TM-TR
6015 C2=P/(2*3.14159265#*K*TH)
6100 C0 = C1/C2
6110 LU=0
6120 GOSUB 7000
6130 LL=-PL
6140 ER=ABS(LL)/10000
6150 FOR J1=1 TO 100
6160 L1=(LL+LU)/2 - ER
6170 L2=(LL+LU)/2 + ER
6175 LA=L1
6176 GOSUB 6300
6180 W1=WI
6181 REM PRINT "W1=";W1
6185 LA=L2
6186 GOSUB 6300
6190 W2=WI
6191 REM PRINT "W2=";W2
6200 IF W1>=W2 THEN LET LU=L2
6210 IF W2>W1 THEN LET LL=L1
6211 REM PRINT "LL=";LL;"LU=";LU
6220 IF ((LU-LL)/ABS(LL)) < .05  THEN GOTO 6250
6230 NEXT J1
6240 PRINT "FAILURE TO FIND WELD BEAD WIDTH AFTER 100
ITERATIONS"
6250 BW = (W1+W2)/2 :REM ** (NONDIMENSIONAL) **
6260 RETURN
6300 REM *** SUBROUTINE FOR FINDING PUDDLE WIDTH FOR GIVEN
6305 REM     LONGITUDINAL POSITION USING NEWTON-RAPHSON
TECHNIQUE ***
6310 REM ** ENTER INITIAL ESTIMATE **
6320 WI=EXP(-C0)
6330 FOR J3 = 1 TO 100
6340 BA=SQR(LA^2+WI^2)
6350 GOSUB 1500
```

```
6360 GOSUB 5100
6370 F = C0*EXP(LA) - K0
6380 DF = 2*K1*WI/BA
6390 WN = WI-F/DF
6400 IF WN <= 0 THEN LET WI=WI/2
6410 IF WN > 0 THEN LET WI=WN
6420 IF ABS(F/DF/WI) < .01 THEN GOTO 6450
6430 NEXT J3
6440 PRINT "FAILURE TO FIND PUDDLE WIDTH AFTER 100 ITERATIONS"
6450 RETURN

7000 REM *** SUBROUTINE TO FIND TIP OF MELT ISOTHERM TAIL ***
7050 REM *** BASED ON NEWTON-RAPHSON SEARCH TECHNIQUE ***
7110 BA = 1
7120 FOR J2=1 TO 100
7130 GOSUB 1500
7140 F1 = EXP(BA) * K0 - C0
7150 GOSUB 5100
7160 DF = EXP(BA) * (K0-K1)
7170 B1 = BA - F1/DF
7180 IF B1 < 80 AND B1 > 0 THEN LET BA = B1
7190 IF B1 > 80 THEN LET BA = (BA+80)/2
7200 IF B1 <= 0 THEN LET BA = BA/2
7210 IF (ABS(F1/DF)/BA) < .001 THEN GOTO 7240
7220 NEXT J2
7230 PRINT "FAILURE TO FIND MAX. DISTANCE FROM SOURCE TO MELT
ISOTHERM"
7240 PL=BA
7250 RETURN
```