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THEORETICAL MODEL OF THE EFFECT OF CRACK TIP BLUNTING ON THE ULTIMATE TENSILE STRENGTH OF WELDS IN 2219-T87 ALUMINUM

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THEORETICAL MODEL OF THE EFFECT OF CRACK TIP BLUNTING ON THE ULTIMATE TENSILE STRENGTH OF WELDS IN 2219-T87 ALUMINUM

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ABSTRACT

A theoretical model representing blunting of a crack tip radius through diffusion of vacancies is presented. The model serves as the basis for a computer program which calculates changes, due to successive weld heat passes, in the ultimate tensile strength of 2219-T87 aluminum. In order for the model to yield changes of the same order in the ultimate tensile strength as that observed experimentally, a crack tip radius of the order of .001 microns is required. Such sharp cracks could arise in the fusion zone of a weld from shrinkage cavities or decohered phase boundaries between dendrites and the eutectic phase, or, possibly, from plastic deformation due to thermal stresses encountered during the welding process.

Microstructural observations up to X2000 (resolution of about .1 micron) did not, in the fusion zone, show structural details which changed significantly under the influence of a heat pass, with the exception of possible small changes in the configuration of the interdendritic eutectic and in porosity build-up in the remelt zone.

INTRODUCTION

The ultimate strength for a variable polarity plasma arc butt weld in 3/8-inch plate of 2219-T87 aluminum has been found[1], by experiment, to increase when additional weld heat passes at lower power are made over the weld. Weld heat passes follow the same path as the original weld, but re-melt only a portion of the cast material in the fusion zone as shown in Figure 1a, b, c, d. Yield stress has been found to decrease during the same experimental procedure. The magnitude of these changes, obtained from tensile tests, is shown in Figure 2[1].

This paper presents a theoretical model which indicates that, in the critical region where fracture tends to propagate, coarsening of crack tip radii by a diffusion process which takes place during weld heat passes is feasible and can contribute to increase in ultimate tensile strength.

Characteristics of the physical process of fracture, especially in aluminum, have been studied, using the kinetic theory of materials, for over twenty years. Two review articles [2,3] describe work at the A.F. Ioffe Physico-Technical Institute USSR Academy of Sciences, Leningrad, where over one hundred materials were tested, by 1970, for confirmation of the applicability of kinetic theory to the failure process. Materials tested included both metal and non-metallic materials, single and polycrystalline materials, alloys, composites, and polymers. By 1980, there, the fracture process during creep tensile tests for aluminum had, through the use of relative density measurements accurate to 10^{-5}, through the use of electron microscopy, x-ray diffraction, et. al., been shown to include, at fracture, large numbers of sub-microscopic discontinuities ($>10^{7}/cm^{3}$) of length less than one-half micron and large numbers or microscopic discontinuities ($>10^{6}/cm^{3}$) of length greater than 1/2 micron in the lateral surface of the test specimen[4]. Creep tests[5], were performed on polycrystalline aluminum (99.96%) in the temperature range 18-300^{o}C and stress range 1-7 kg/mm^{2}. Specimens were loaded for different times and then unloaded to study the build-up kinetics of microdiscontinuities. Researchers at AFIPTI report that rupture during creep develops from "atomic" cracks which arise after the application of the load, grow rapidly, become blunted, and may even change into stable void-shaped discontinuities not larger than 1 μm by the end of the first stage. The mechanism for crack blunting, the mechanism for variations in microcrack concentration in the volume and in surface layers[6], and the mechanism for coalescence of cracks and voids is a diffusion process most probably involving the emission of vacancies from breaks in continuity to sinks[7]. This paper restricts discussion to the role that diffusion of vacancies might have in blunting of crack tip radii. The reader is referred to related papers [8-14] which discuss the role of dislocations, the role of original microporosity, and the role of hydrostatic pressure in fracture kinetics which also contain materials which supports the feasibility of the process considered in this paper.

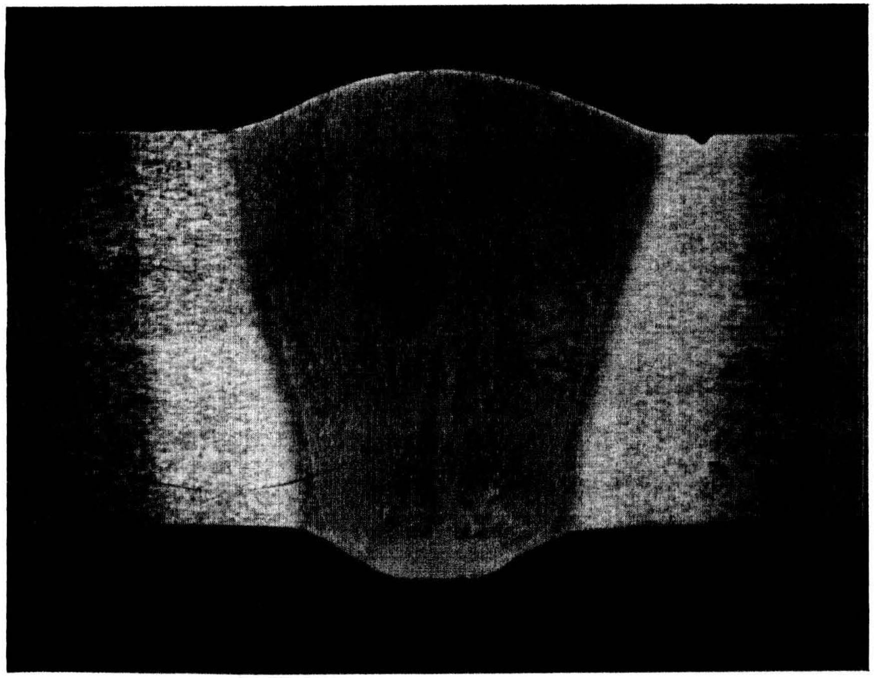

Figure 1a. Initial Weld Cross-Section. Current= 190 amps., Voltage= 31 volts, Weld Speed=7.3ipm 1/16 dia. 2319 wire feed= 60 ipm/, Plate Thickness= 3/8 in.

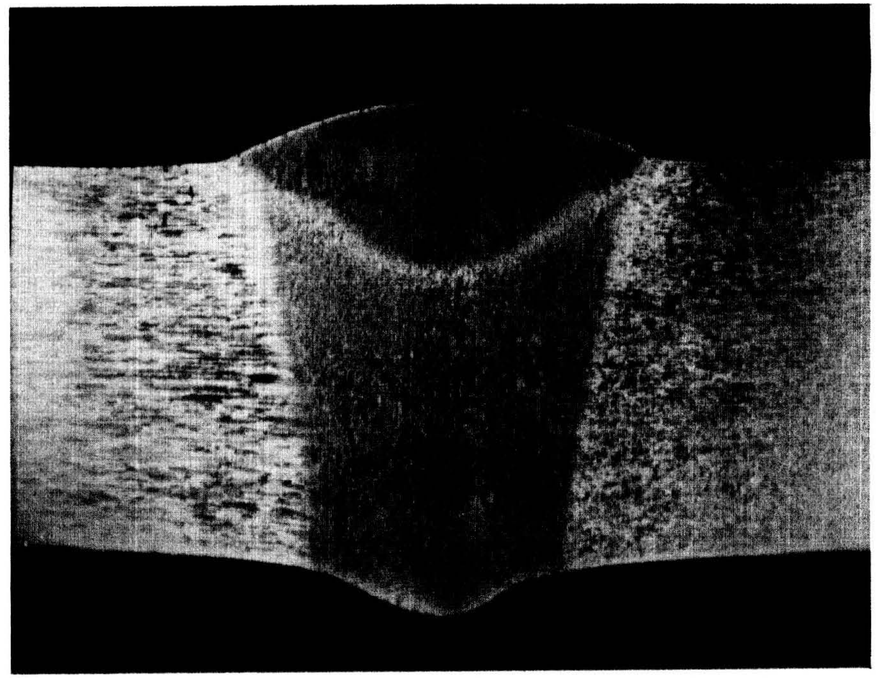

Figure 1b. First Weld Heat Pass Cross-Section.
Current = 175 amps.
Voltage = 28 volts
Weld Pass Speed = 9 ipm.
No Wire Feed

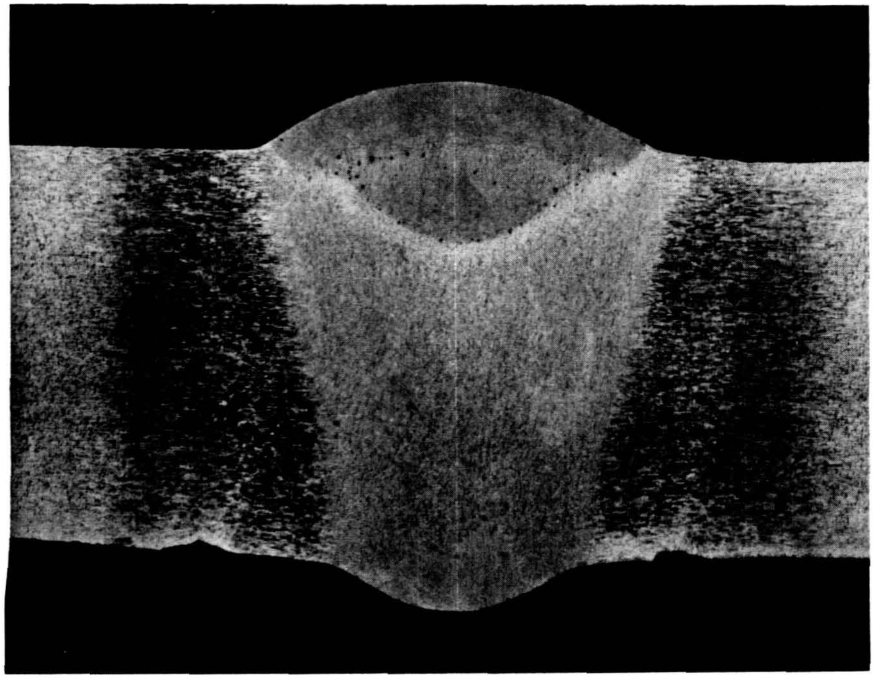

Figure 1c. Second Weld Heat Pass
Cross-Section.
Current= 175 amps.
Voltage= 28 volts
Weld Pass Speed= 9 ipm.
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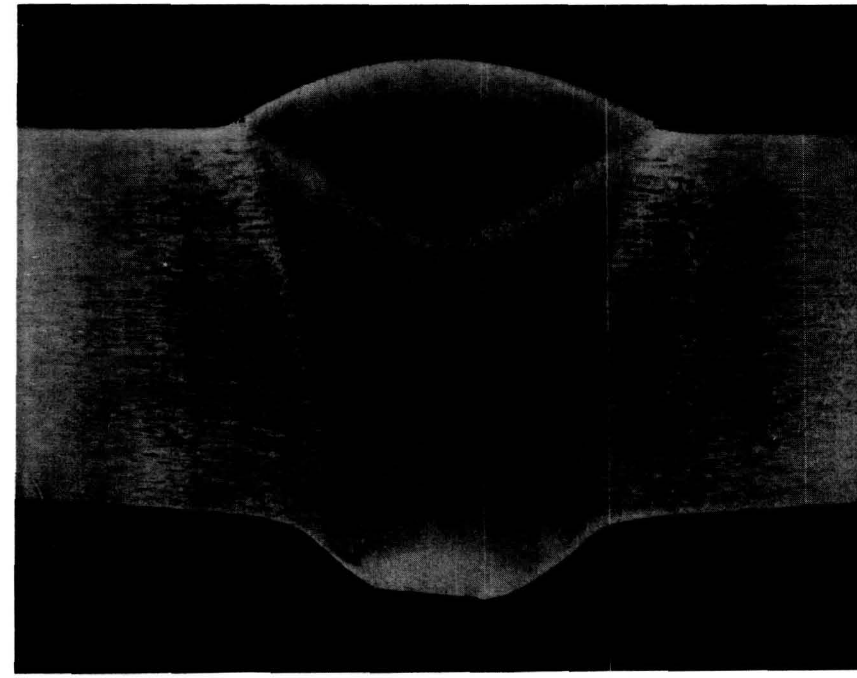


Figure 1d. Third Weld Heat Pass
Cross-Section.
Current= 175 amps.
Voltage= 28 volts
Weld Pass Speed= 9 ipm.
No Wire Feed

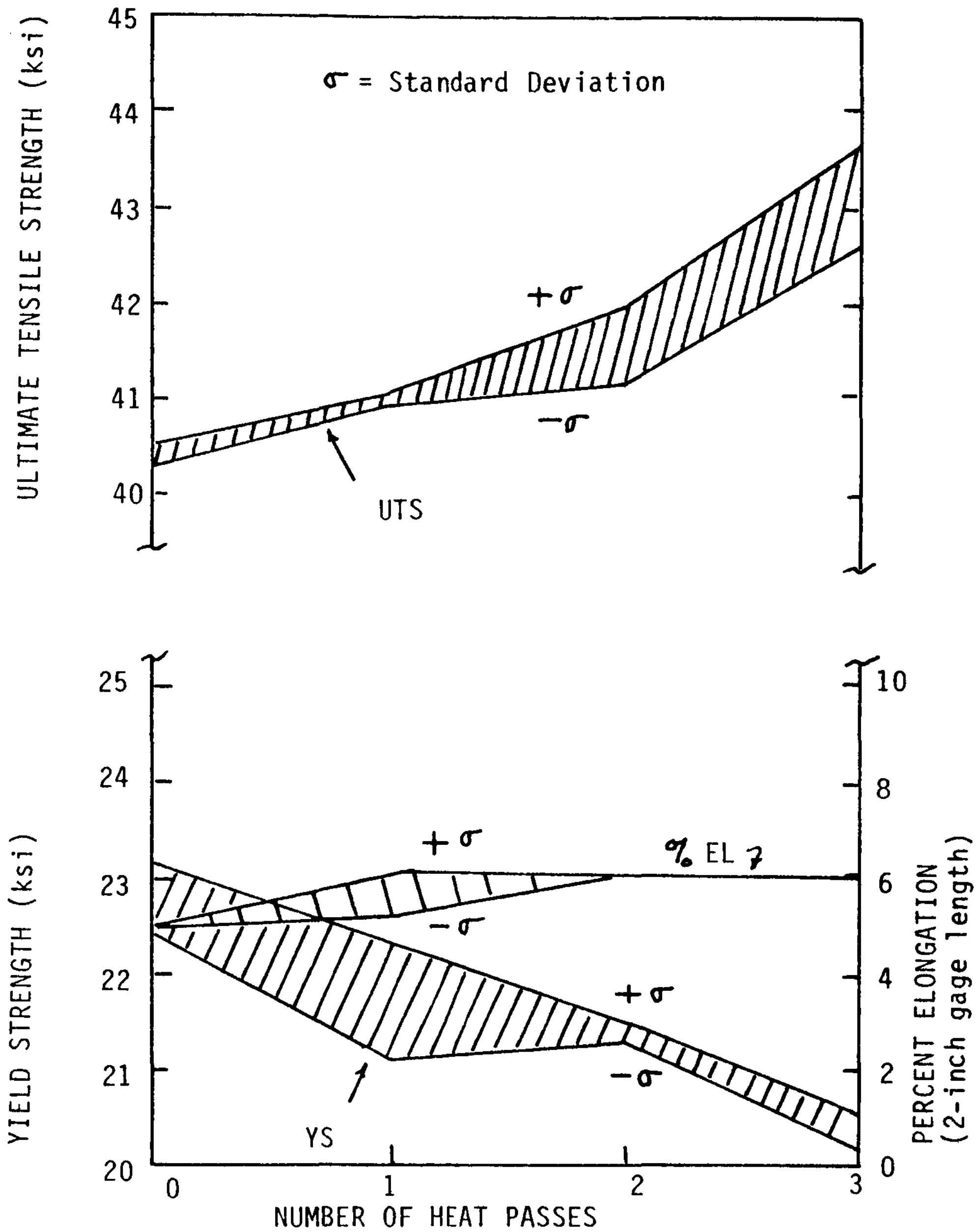


Figure 2. Effect of Mutiple Heat Passes on the Strength of a Variable Polarity Plasma Arc Butt Weld in 3/8-inch 2219-T87 Aluminum Plate.

THEORETICAL MODEL

If the local temperature is high enough at a crack tip where the radius of curvature is small and the vacancy concentration is high, vacancies with diffuse to volumes of lower vacancy concentration. They may migrate through the bulk material to other voids or to flat surfaces. It is assumed that the elliptical crack considered is fairly flat at the ends of its minor axis so that vacancies will not need to travel further than half the crack length. The diffusion process increases the radius of the crack tip (blunting or coarsening). It is assumed that the vacancy flow will have little effect on the relatively flat portion of the crack. The diffusion concept is used in Appendix A to develop the differential equation

$$\frac{d\sigma_u}{\sigma_u} = \frac{\Omega(\pi-\alpha)C_o\left(e^{\frac{\gamma\Omega}{kTR}}-1\right)D_s}{4R^2\left[\tan\left(\frac{\pi-\alpha}{2}\right)-\left(\frac{\pi-\alpha}{2}\right)\right]\ln\frac{L}{R}}\,dt$$

where σ_u is the local ultimate stress

α is the coarsening angle firmed by tangents drawn to the assumed circular crack tip

C_o is the equilibrium concentration of vacancies at the local temperature

T is the local temperature

R is the crack dip radius

D_s is the self diffusion coefficient of aluminum

t is the time

Ω is the atomic volume of fcc aluminum

L is half the crack length

γ is the surface energy of fcc aluminum.

The above formula, the following differential equation, also derived in Appendix A,

$$\frac{d\sigma_u}{\sigma_u} = \frac{dR}{2R} ,$$

and a record of the history of the local temperature during the diffusion process[18] form a system of equations which through iterative calculations determine the local ultimate strength and crack tip radius as a function of time.

Estimate of $\alpha/2$

If a line is drawn tangent to the ellipse shown in Figure 3, then

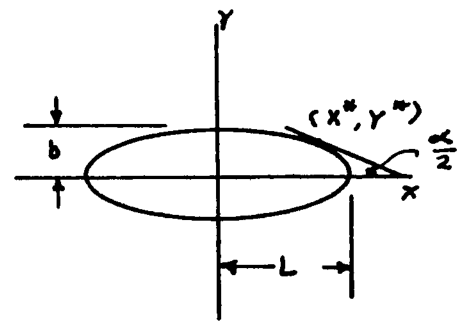


FIGURE 3

Assuming that $b \simeq y^*$ and that L is much larger than the radius, R, of curvature of the ellipse at the point (L,0), so that

$$L \approx x^* \text{ and } R \simeq b, \text{ then}$$
$$\text{TAN}\,\alpha/2 = R/L$$

Calculation of Atomic Volume

The lattice parameter for fcc aluminum is $4.04(10^{-8})$cm. Hence, the cell volume is $65.94(10^{-24})cm^3$ which accommodates four atoms. Thus the atomic volume is $16.48(10^{-24})cm^3$/atom.

The Self-Diffusion Coefficient, Surface Energy, and Equilibrium Vacancy Concentration

Volin and Balluffi[16] determined, as a consequence of study of the annealing kinetics of voids in aluminum, that the self diffusion coefficient of aluminum was

$$D_S = .176 \text{ Exp } (-1.31 \text{ ev/kT}) \text{ cm}^2 \text{ S}^{-1}$$

in the temperature range 85-209^{o}C, which satisfactorily agreed with the work of Lundy and Murdock, and which agrees satisfactorily with the work by Bass describing the formation and motion energies of vacancies in aluminum[17]. The surface energy of aluminum is taken as 1500 ergs/cm^2 as in the paper by Volin and Balluffi even though calculations suggest that the figure might be slightly lower.

Bass lists the formation energy of a vacancy in aluminum as .76 $\pm$ 0.02 eV and the equilibrium vacancy in aluminum as

$$C = C_0 \text{ EXP } (.76 \pm .02 \text{ eV/kT})$$

where $C_0 = 10^{24}/16.48 \text{ cm}^{-3} = 6.066\ (10^{22})\ \text{cm}^{-3}$

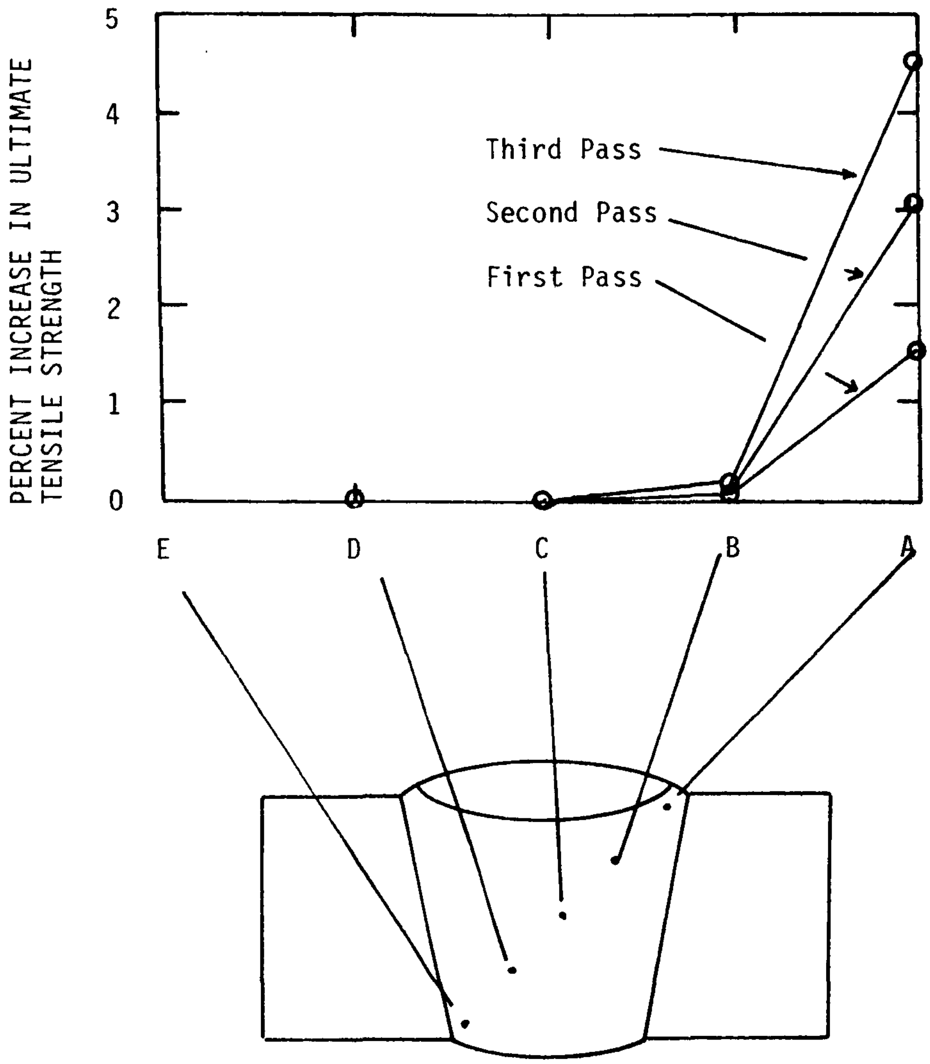
k = Boltzmann's constant = $8.611\ (15^{-5})$ eV/^{o}K

and T is the temperature in degrees Kelvin.

Temperature History

The Portion of the computer program which calculates the local temperature as a function of time was developed by Dr. A. C. Nunes, Jr. using a moving point source along with a moving line source to model the heat input. Non-conductive heat losses can be adjusted so that the width of the remelt zone of the fusion zone can be matched.

Five points equally spaced along a line from the edge of the crown to the edge of the root on the opposite side of the fusion zone, as shown in Figure 4, were chosen as local points for calculation. Tensile test specimens show that fracture tends to occur along that line. Point A was taken to be just outside the remelt zone. The computer model for calculating temperature predicted temperatures too high at Point B when non-conductive losses were used to match the width of the remelt zones shown in Figure 1. Hence, higher non-conductive losses were assumed so that the calculated width of the remelt zone was reduced. For the newly calculated remelt zone, the circular part of the remelt zone was slightly larger, but still circular, and the shortest distance of the remelt zone from Point B remained the same. Temperatures for Points B, C, D, and E were calculated using the adjusted parameters. It is felt that this correction gave realistic results for the temperature distribution.



WELD LOCATION

Crack Tip Radius= 20 Å (.002 μm)

Crack Length= 1000 Å (.100 μm)

Figure 4. Calculated Effect of Heat Pass on Local Ultimate Tensile Strengths Within the Primary Fusion Zone of a Variable Polarity Plasma Arc Butt Weld in 3/8-inch 2219-T87 Aluminum Plate

DISCUSSION

The amount of coarsening of the crack tip radius and the resulting change in ultimate strength during a weld heat pass is particularly sensitive to

* the sharpness of the crack tip and,
* the shape and magnitude of the local temperature versus time curve.

Significant coarsening occurs, due to short heating times, only above temperatures of approximately 650°K or 680°K for crack tip radii of 10Å or 50Å respectively. Hence, significant improvement in local ultimate tensile strength takes place at only Points A, B, and possibly C of Figure 4.

The local ultimate tensile strength of Points A, B, C, D and E are not likely to be identical immediately after the initial weld since the cooling rate is different for each of those points. This non-homogeneity does not complicate calculations since the configuration of the system of equations to be used and the iterative process used produce the relative change in ultimate tensile strength. Figure 4 illustrates the percentage relative change at the various points for a crack tip of 20Å, about four times the lattice dimension of fcc aluminum. The relationship of these changes to changes in ultimate strength observed experimentally is shown in Figure 5, where only the increase in the local ultimate strength at Point A matched the observed values. The 20Å initial crack tip radius, which provides significant increase in local ultimate tensile strength, is of a size large enough to be observed by the transmission microscope. Preliminary, but extensive, scanning electron microscopy was utilized at powers up to 2000X with good resolution to observe the microstructure of the weld cross section. Micrographs representing the general areas near Points A, B, C, D and E are shown in Figures 6a, b, c, d, and e for a cross section of the fusion zone on a specimen not subjected to weld heat passes. Obviously, 2000X is not enough magnification to see the thin sharp cracks pertinent to this discussion. Replication techniques will permit use of the transmission microscope, which can yield the desired magnification. The micrographs do reveal the dendritic structure in the cast material and the interdentritic eutectic which is a mixture of $CuAl_2$ and α-aluminum. Microprobe analysis also reveals that a copper depleted zone occurs next to the eutectic similar to those mentioned by Doig and Edington.[19] One can realistically surmise that at the edge of the crown of the weld, where Point A is taken, and where the interdendritic eutectic appears normal to the surface of test speciman, see Figure 6a, cracks of submicroscopic dimensions may initiate in the copper depleted zone after welding. Coarsening of the crack tip radii of these types of cracks, large numbers of which may form during plastic flow prior to fracture under tensile loading, may contribute to the increase in ultimate tensile strength.

It appears, however, that the increase in ultimate strength may be due to more than one mechanism. Ultimate tensile strength increases whether or not the remelt zone overlaps the crown "corner" of the weld or previous weld pass. Hence, refinement of the dendritic structure in the remelt zone, due to more rapid cooling because of lower power, may also contribute to increase in ultimate strength. Further, reconfiguration of the interdendritic eutectic, possibly diffusing into the copper depleted zone or reforming through self diffusion, a slight variation noted in the micrograph study, may play a role in the process.

Coarsening of crack tap radii, then, represents a feasible, but still not certain, or partial explanation, of multiple heat pass strengthening. The process itself is of sufficient practical importance, in fracture mechanics, to be worth investiagation in its own right. Although progress has been made, further work is still necessary to pin down the mechanism of multiple heat pass strengthening.

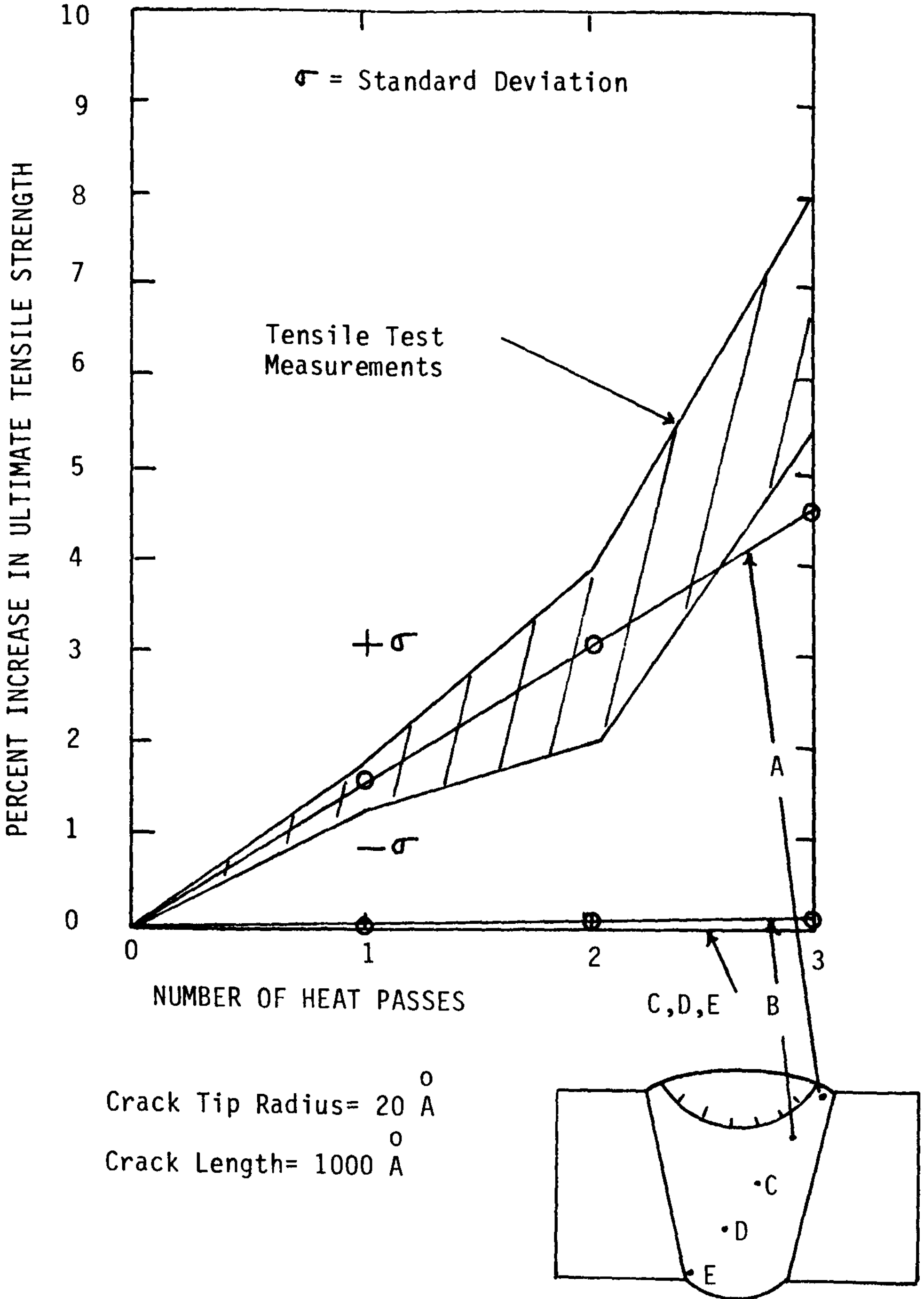


Figure 5. Calculated Effect of Heat Passes on Local Ultimate Tensile Strengths Within the Primary Fusion Zone of a Variable Polarity Plasma Arc Butt Weld in 3/8-inch 2219-T87 Aluminum Plate.

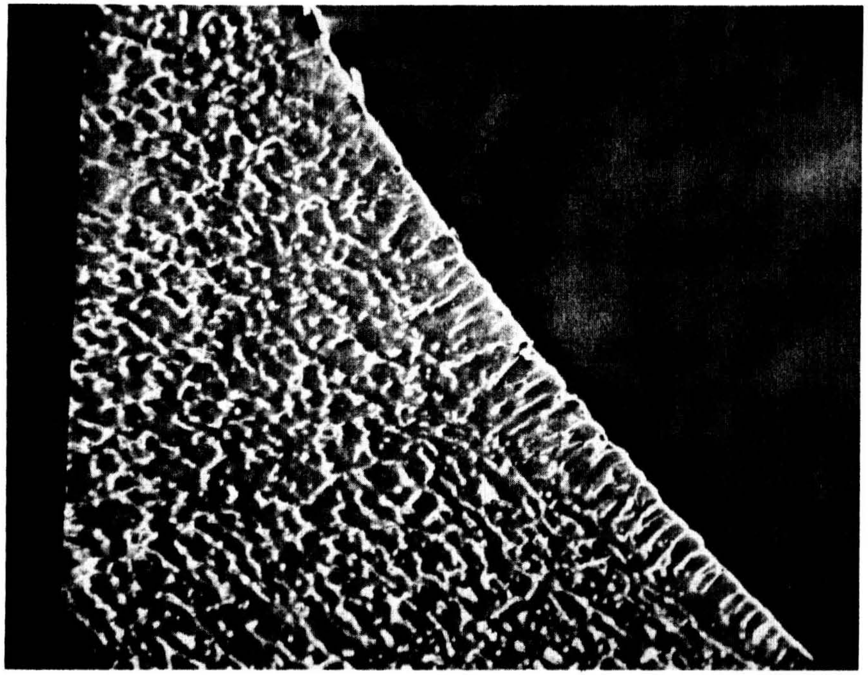


Figure 6a. Point A, Initial Weld.
200X
Alumina Polish
Keller's Etch

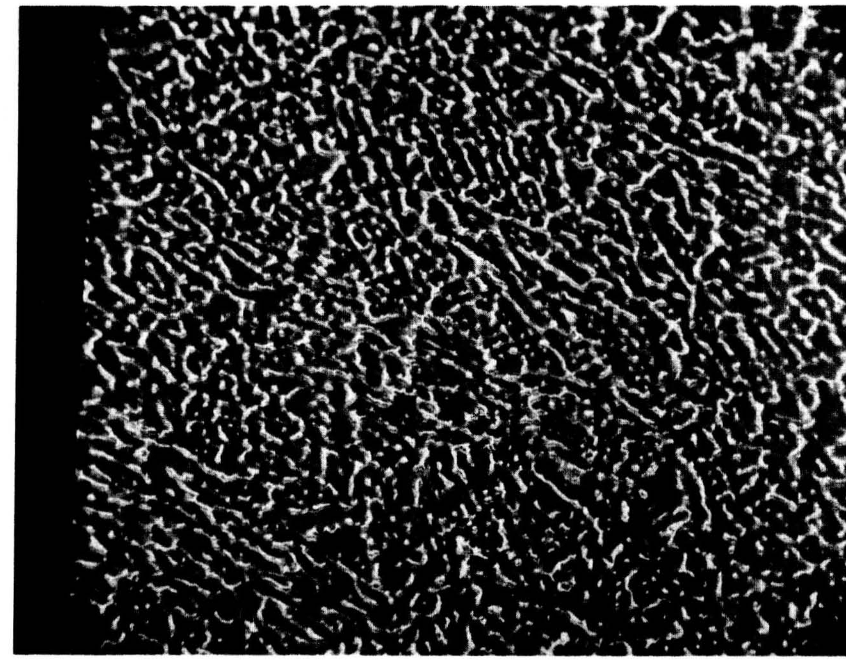


Figure 6b. Point B, Initial Weld.
200X
Alumina Polish
Keller's Etch

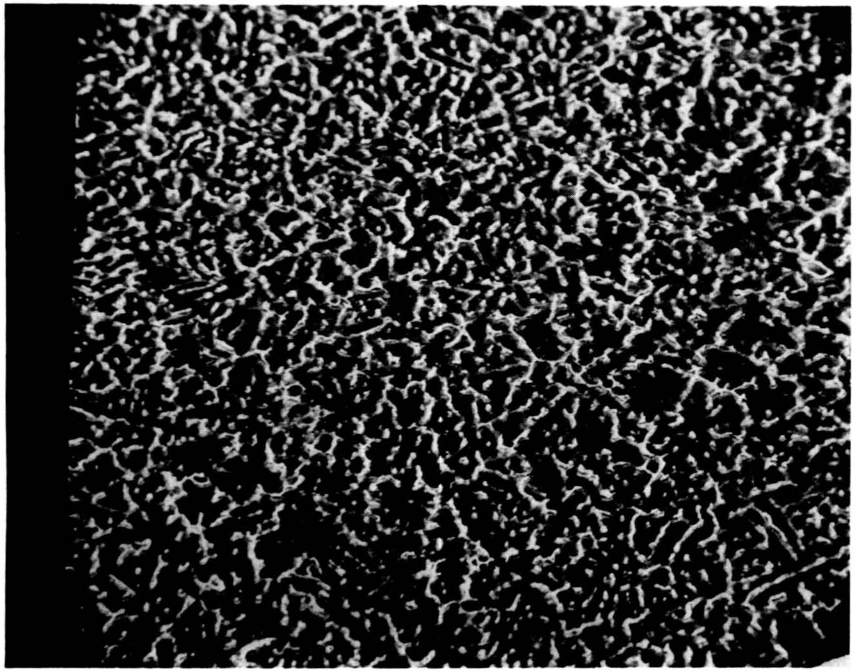


Figure 6c. Point C, Initial Weld
200X
Alumina Polish
Keller's Etch

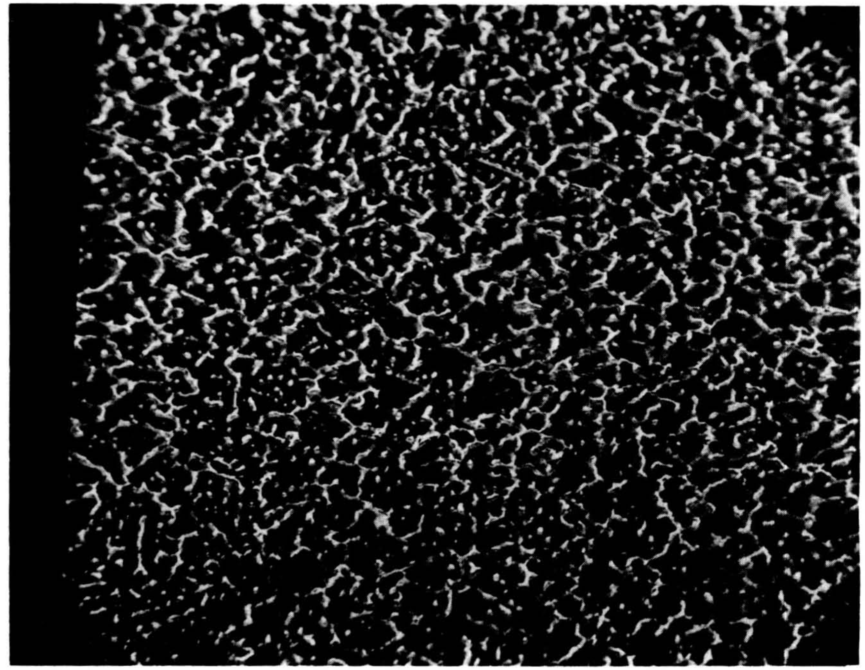


Figure 6d. Point D, Initial Weld.
200X
Alumina Polish
Keller's Etch

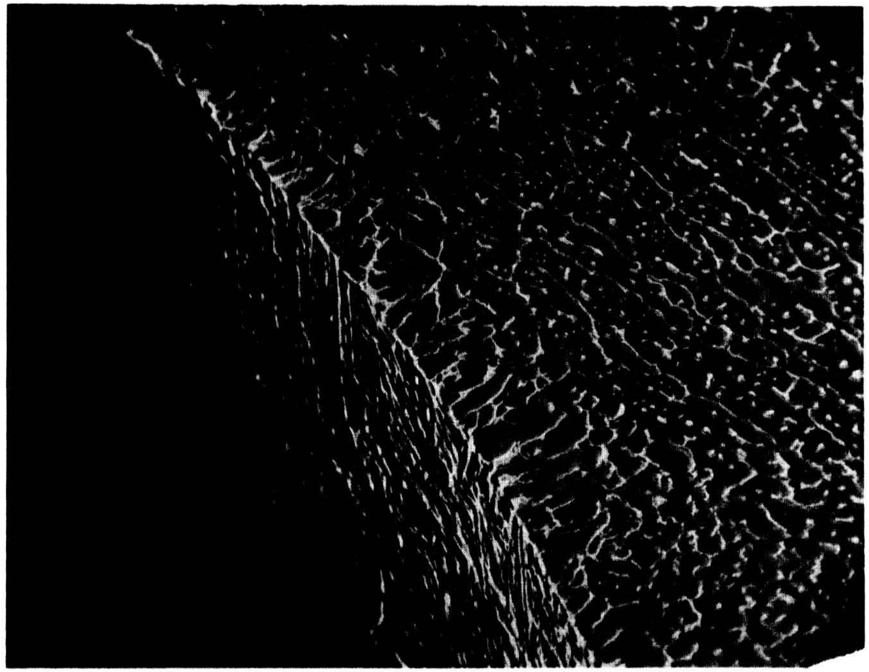


Figure 6e. Point E, Initial Weld.
200X
Alumina Polish
Keller's Etch

RECOMMENDATIONS

The following proposed theoretical and experimental research will help in identifying those processes which characterize fracture and increase ultimate strength in welded 2219-T87 aluminum.

*...to better understand the fracture process. Proposed experimental research should include microscopic examination, both low power, SEM, and replication TEM, of cross sections of the weld of tensile tested specimens. Test specimens should be loaded to a particular stress, held at that stress for a period of time, unloaded, and examined. This test procedure may allow identification of critical areas where cracks nucleate and characterize the growth pattern to failure.

*...establish a more accurate method to determine the local temperature history. Higher order multipoles could improve the present technique. Finite element methods, allowing a variable thermal conductivity throughout the material, have been formulated for solution of boundary value and initial value problems to determine local temperature history such as needed in the paper. Since microstructural processes are so sensitive to local temperature history, computer software should be obtained, if it exists, or developed to determine local temperatures more accurately. Some measurements needed just to set up analyses such as loss parameters are not known. However, checks against the program could be verification by thermocouple readings near the weld and the pattern of the remelt zone after weld heat passes.

*...to understand the effect of a refined dendritic pattern in the remelt zone after weld heat passes. A theoretical and experimental study should be made of the relationship of the size of the dendritic structure with respect to ultimate stress. The size of the dendritic structure can be varied by varying the weld parameters of weld heat passes or by varying the quenching rate of the material during welding or weld heat passes.

*...to better understand the role of the inter-dendritic eutectic. The diffusion coefficient of copper in aluminum is known as a function of temperature. Hence, various, mechanisms, possibly self-diffusion within the eutectic, or diffusion of copper back into the copper depleted zone as a function of time and temperature might be checked experimentaly by heat treatment of cast material from the weld fusion zone and subsequent microscopic examination.

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APPENDIX A

EFFECT OF DEFECT EDGE RADIUS COARSENING ON ULTIMATE TENSILE STRENGTH

The preliminary version of the analysis was prepared by Dr. A. C. Nunes, Jr.

Ductile fractures generally occur by coalescence of voids within the fracturing material. Voids often form around defects such as cracks or weakly bonded second phase particles. The limitation on the ultimate tensile stress, σ_u, is set by the critical stress for propagation of internal voids. The maximum stress supportable by the defects within the metal should be that for initiation of a void from the defect.

If the defect has a sharp edge of suitable orientation, the concentration of stress at the edge should be where the void starts. The stress concentration for an ellipsoidal crack of length $2c$ and radius of curvature ρ at the crack edge raises the nominal stress σ_n to a higher local effective stress σ_e according to the Inglis relation:

$$\sigma_e = 2\,\sigma_n \sqrt{\frac{c}{\rho}}$$

Assuming that the nominal stress becomes the ultimate tensile strength at a critical value of σ_e, σ_{ec} then

$$\sigma_u = \frac{\sigma_{ec}}{2}\sqrt{\frac{\rho}{c}}$$

If the radius of the sharp edge of the defect changes, the ultimate tensile strength changes, then, according to the relation:

$$\frac{d\sigma_u}{d\rho} = \frac{\sigma_u}{2\rho}$$

If two faces of a defect come together at angle α to a radius ρ as shown in Figure A-1, then a loss of defect volume at the edge would result in a change of radius $\Delta\rho$.

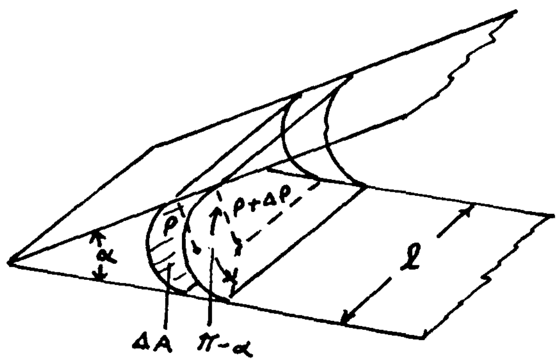

FIGURE A-1. EDGE OF A DEFECT SHOWING CHANGE OF RADIUS OCCURRING WITH LOSS OF VOLUME ΔV

The shaded area, ΔA can be shown to be

$$\Delta A = \{2\rho\Delta\rho + (\Delta\rho)^2\}\{\cot(\alpha/2) - (\pi-\alpha)/2\}$$

so that
$$\frac{dV}{d\rho} = 2\ell\rho\{\cot(\alpha/2) - (\pi-\alpha)/2\}$$

disregarding second order terms.

The kind of volume reduction at the defect edge shown in Figure A-1 takes place because of a difference in chemical potential, $\Delta\mu$, for solutes (or vacancies) on surfaces of different curvature. When a solute atom or vacancy moves from a cylindrical surface of radius ρ_1 to one of radius ρ_2 causing a volume loss Ω to the first cylinder and a volume gain of Ω to the second, a net change ΔA in surface area results

$$\Delta A = \Omega\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)$$

If the surface energy of the cylinders is γ per unit area then the chemical potential difference between the surfaces is:

$$\Delta\mu = \gamma\Omega\left(\frac{1}{\rho_2} - \frac{1}{\rho_1}\right)$$

Assuming that the activity of the solute or vacancy is proportional to its concentration, then the equilibrium concentration C_ρ at the curved surface is related to the equilibrium concentration C_∞ at a flat surface $(\rho = \infty)$ according to the equation:

$$C_\rho / C_\infty = e^{\frac{\gamma\Omega}{kT\rho}}$$

It is further assumed here that the surface reaction rates are fast enough so that equilibrium concentrations are maintained at the surfaces and that the relatively lengthy time required for diffusion of solute atom or vacancy from regions of high concentration to regions of low concentration is what holds back the coarsening process.

Fick's first law relating mass flux $\dot{j}$ in atoms or vacancies per area per unit time to the concentration gradient in the radial direction r is assumed to hold:

$$\dot{j} = -D\frac{\partial c}{\partial r}$$

where D is the solute or vacancy diffusivity.

A steady cylindrically symmetrical flow of $\dot{m}$ atoms or vacancies per unit time yields a flux:

$$\dot{j} = \frac{\dot{m}}{2\pi r\ell}$$

Which, with Fick's first law, requires a concentration C_r varying with the radius according to the relation:

$$C_r = C_\rho - \frac{\dot{m}}{2\pi\ell D}\ln\left(\frac{r}{\rho}\right)$$

Where C_ρ is the concentration at radius ρ.
Hence:

$$\dot{j} = \frac{D(C_\rho - C_r)}{r\ln\left(\frac{r}{\rho}\right)}$$

Assuming that there is so much more flat surface ($\rho = \infty$) than curved edge that the bulk mean solute or vacancy concentrate C_o is determined by the flat surface, then:

$$C_\rho - C_r \simeq C_\rho - C_o$$

for large r and

$$C_\rho - C_o \simeq C_o \left(e^{\frac{\gamma \Omega}{kT\rho}} - 1 \right)$$

The loss of volume v from the sharp edge of a defect is given by:

$$\frac{dv}{dt} = \Omega (\pi - \alpha)\, r\, \ell\, j$$

or

$$\frac{dv}{dt} = \frac{\Omega (\pi - \alpha)\, \ell\, D C_o \left(e^{\frac{\gamma \Omega}{kT\rho}} - 1 \right)}{\ln (L/\rho)}$$

Where L is half the crack length and assumed an approximate maximum upper bound distance to a flat surface.

The ultimate tensile strength then varies according to the relation:

$$\frac{d\sigma_u}{dt} = \frac{d\sigma_u}{d\rho} \cdot \frac{d\rho}{dV} \cdot \frac{dV}{dt}$$

so that

$$\frac{d\sigma_u}{\sigma_u} = \frac{\Omega (\pi - \alpha)\, C_o \left(e^{\frac{\gamma \Omega}{kT\rho}} - 1 \right) D}{4\rho^2 \left\{ \cot \frac{\alpha}{2} - \frac{(\pi - \alpha)}{2} \right\} \ln \left(\frac{L}{\rho} \right)}\, dt \; .$$

APPENDIX B

```
10 REM *** RAPID DIFFUSSION ANNEALING ***
20 REM *** INCREASE IN ULTIMATE STRENGTH ***
30 CLEAR
35 PRINT "INPUT 1 IF MAX PRINTED OUTPUT WANTED, 0 OTHERWISE."
36 INPUT PU
40 PRINT "THIS PROGRAM CALCULATES INCREASED ULTIMATE"
50 PRINT "STRENGTH DUE TO RAPID DIFFUSION ANNEALING"
52 PRINT "(BLUNTING) OF MICROCRACKS. TEMPERATURES AT"
54 PRINT "A MATERIAL POINT ARE TO BE ENTERED FOR DISCRETE"
56 PRINT "TIMES OR CALCULATED FROM THE ATTACHED SUBROUTINE."
60 PRINT
62 PRINT "INPUT 0 TO SKIP ALL PRINTING EXCEPT THE LAST."
63 PRINT "INPUT 1 TO GET TEMP , POINT DATA, ET. AL."
64 INPUT ZA
70 PRINT "ENTER 0 IF THE SUBROUTINE IS TO BE CALLED."
72 PRINT "ENTER 1 OTHERWISE"
80 INPUT B
81 PRINT "INPUT THE NUMBER OF HEAT PASSES NOT INCLUDING THE WELD PASS."
82 INPUT WP
83 PRINT "INPUT NPTS-1 ACROSS THE DIAGONAL."
84 INPUT LU
85 DELETE UP,RP,TU,TR
86 DIM UP(WP,LU),RP(WP,LU)
87 DIM TU(WP,LU),TR(WP,LU)
88 FOR II=0 TO WP
90 IF B=1 THEN 2030
200 REM *** HAZ TEMPERATURE HISTORY ***
210 REM *** DATA INPUT ***
230 PRINT "PLEASE SELECT THE NUMBER OF THE METAL TO BE WELDED"
240 PRINT "FROM THE LIST BELOW."\PRINT\PRINT\PRINT
250 PRINT "0. UNLISTED METAL"\PRINT
260 PRINT "1. 2219 ALUMINUM"\PRINT
270 PRINT "2. 302 STAINLESS STEEL"\PRINT
280 PRINT "3. 321 STAINLESS STEEL"\PRINT
290 PRINT "4. INCONEL 718"\PRINT
300 INPUT Q
310 IF Q=1 THEN 550
320 IF Q=2 THEN 570
330 IF Q=3 THEN 590
340 IF Q=4 THEN 610
350 PRINT "WHAT IS THE METAL TO BE WELDED?"\PRINT\PRINT\PRINT
360 INPUT M$
370 PRINT "PLEASE WRITE IN THE LOWER AND UPPER LIMITS OF THE MELTING"
380 PRINT "TEMPERATURE RANGE OF THE ALLOY TO BE WELDED. USE UNITS OF"
390 PRINT "DEGREES FAHRENHEIT. SEPARATE THE TWO VALUES BY A COMMA."
400 PRINT "NOTE: A GOOD SOURCE REFERENCE FOR THIS KIND OF DATA IS THE"
410 PRINT "AEROSPACE STRUCTURAL MATERIALS HANDBOOK."\PRINT\PRINT\PRINT
420 INPUT LT,UT
430 PRINT "WHAT IS THE THERMAL CONDUCTIVITY OF THE ALLOY IN BTU'S PER"
440 PRINT "HOUR PER FOOT PER DEGREE FAHRENHEIT?"\PRINT\PRINT\PRINT
450 INPUT K1
460 LET K1=K1*2.441E-05
470 PRINT "WHAT IS THE SPECIFIC HEAT OF THE ALLOY IN BTU'S PER LB"
480 PRINT "PER DEGREE FAHRENHEIT?"\PRINT\PRINT\PRINT
490 INPUT C1
500 PRINT "WHAT IS THE DENSITY OF THE ALLOY IN LBS PER CUBIC INCH?"
510 PRINT\PRINT\PRINT
520 INPUT RO
530 LET A1=K1/RO/C1*56.83
540 GOTO 630
550 LET UT=1190\LET LT=1010\LET K1=2.44E-03\LET A1=5.56
560 LET M$="2219 ALUMINUM"\GOTO 630
570 LET UT=2650\LET LT=2550\LET K1=4.27E-04\LET A1=.5
580 LET M$="302 STAINLESS STEEL"\GOTO 630
590 LET UT=2550\LET LT=2500\LET K1=4.03E-04\LET A1=.66
600 LET M$="321 STAINLESS STEEL"\GOTO 630
610 LET UT=2437\LET LT=2300\LET K1=3.83E-04\LET A1=.71
620 LET M$="INCONEL 718"\GOTO 630
630 PRINT "THE METAL TO BE WELDED IS NOW CHARACTERIZED. WE NOW"
```

```
640 PRINT "TURN TO THE WELDING PROCESS PARAMETERS."\PRINT\PRINT\PRINT
650 PRINT "WHAT IS THE AMBIENT TEMPERATURE OF THE METAL IN DEGREES"
660 PRINT "FAHRENHEIT? IF THE METAL IS PREHEATED, GIVE THE PREHEAT"
670 PRINT "TEMPERATURE AS THE AMBIENT TEMPERATURE."\PRINT\PRINT\PRINT
680 INPUT T0
760 PRINT "PLEASE SPECIFY WELD POWER IN KILOWATTS."
770 PRINT\PRINT\PRINT
780 INPUT P0
790 PRINT "PLEASE SPECIFY WELD SPEED IN INCHES PER MINUTE."
800 PRINT\PRINT\PRINT
810 INPUT V1
820 PRINT "WHAT PERCENT OF TOTAL BEAM POWER IS LOST FROM THE WELD"
830 PRINT "PUDDLE DUE TO PROCESSES OTHER THAN CONDUCTION BY THE PLATE?"
840 PRINT "THESE LOSSES INCLUDE RADIATION AND METAL EVAPORATION FROM"
850 PRINT "THE VICINITY OF THE PUDDLE."\PRINT\PRINT\PRINT
860 INPUT F1
861 PRINT "INPUT THE NEW NON-CONDUCTIVE PERCENT LOSSES FOR DEEP PTS."
862 INPUT NC
863 CC=F1
870 PRINT "WHAT PERCENT OF THE REMAINING BEAM POWER IS ABSORBED CLOSE"
880 PRINT "TO THE METAL SURFACE SO AS TO FORM THE EB WELD NAILHEAD?"
890 PRINT "THIS WOULD BE THE PERCENTAGE OF THE BEAM CURRENT LACKING"
900 PRINT "SUFFICIENT POWER DENSITY TO VAPORIZE THE METAL."
910 PRINT\PRINT\PRINT
920 INPUT F2
940 DIM KD(150),TS(150),US(150),R(150)
950 IF II<>0 THEN 1140
960 PRINT "PLEASE SELECT LENGTH OBSERVED: 0.5, 2.5, 5, 10, 25 INCHES."
970 PRINT\PRINT\PRINT
980 INPUT XB\LET XB=XB/5\LET XA=-4*XB
990 PRINT "PLEASE SELECT MAXIMUM TEMPERATURE: 1000, 2000, 5000, 10000 DEG
F."
1000 PRINT\PRINT\PRINT
1010 INPUT TG
1020 PRINT "INPUT HALF THE CRACK LENGTH IN CENTIMETERS."
1030 INPUT L
1040 PRINT "INPUT THE LOWER MELTING TEMPERATURE(DEG. KELVIN)."
1050 INPUT LQ
1060 PRINT "INPUT THE RADIUS OF THE TIP OF THE CRACK(CM)."
1070 INPUT R(0)
1080 REM R IS ASSUMED MUCH LESS THAN L
1090 PRINT "INPUT THE ULTIMATE STRESS."
1100 INPUT US(0)
1102 FOR MM=0 TO LV
1103 UP(0,MM)=US(0)
1104 RP(0,MM)=R(0)
1105 NEXT MM
1106 PRINT\PRINT
1110 PRINT "INPUT ONE HALF THE ROOT WIDTH,ONE HALF THE CROWN WIDTH,"
1112 PRINT "AND THE PLATE THICKNESS(DIMENSIONS IN INCHES)."
1120 INPUT BH,TH,W1
1125 DELETE YY,ZZ,MU,MR,SU,SR
1130 DIM YY(LV),ZZ(LV),MU(LV),MR(LV),SU(LV),SR(LV)
1140 FOR MM=0 TO LV
1145 IF II<>0 THEN US(0)=UP(II,MM)
1146 IF II<>0 THEN R(0)=RP(II,MM)
1150 Y=-BH+(TH+BH)*MM/LV
1160 Z=-W1*(Y-TH)/(BH+TH)
1170 YY(MM)=Y
1180 ZZ(MM)=Z
1190 GOSUB 3000
1200 WAIT 1500
1210 PAGE
2020 GOTO 2130
2030 PRINT "INPUT ONE LESS THAN THE NUMBER OF DISCRETE"
2040 PRINT "TEMPERATURES TO BE CONSIDERED."
2050 INPUT M
2060 DIM KD(M),TS(M)
2070 DIM US(M),R(M)
2080 FOR I=0 TO M
```

```
2090 PRINT "INPUT TEMPERATURE(DEG. KELVIN),TIME(SECONDS)"
2100 INPUT KD(I),TS(I)
2110 NEXT I
2120 GOTO 2220
2130 FOR I=0 TO 150
2140 TA(I)=5*TA(I)/9+255.37
2150 NEXT I
2160 DT=(2*XB)/V1
2170 M=150
2180 FOR I=0 TO 150
2190 KD(I)=TA(150-I)
2200 NEXT I
2290 AL=2*ATN(R(0)/L)
2300 PI=4*ATN(1)
2310 OM=16.48*10^(-24)
2340 PAGE
2341 IF PU=0 THEN 2420
2350 PRINT "Z=";Z;"Y=";Y;"L=";L;"R(0)=";R(0)
2360 PRINT "AL=";AL;"US(0)=";US(0)
2370 PRINT
2380 PRINT "KD(I)        DS      RA      RR      US(I)       R(I)"
2390 PRINT "A            C0      S       D       LG"
2400 PRINT
2410 PRINT
2420 FOR I=1 TO M
2430 IF KD(I)<=LO THEN 2470
2440 US(I)=UP(0,MM)
2450 R(I)=RP(0,MM)
2452 IF ZA=0 THEN 2460
2455 PRINT II;I;MM;KD(I),R(I-1),US(I-1)
2460 GOTO 2610
2470 IF B=0 THEN LET DS=DT
2480 IF B=1 THEN LET DS=TS(I)-TS(I-1)
2490 A=(OM*(PI-AL)*DS)/(4*(SIN((PI-AL)/2)/COS((PI-AL)/2))-((PI-AL)/2))
2500 C0=6.066*10^(22)*EXP(-8478/KD(I))
2502 IF ZA=0 THEN 2510
2505 PRINT II;I;MM;KD(I),R(I-1),US(I-1)
2510 S=EXP(1500*OM/(1.381*10^(-16))/R(I-1)/KD(I))-1
2520 D=.176*EXP(-15213/KD(I))
2530 LG=LOG(L/R(I-1))
2540 RA=A*C0*S*D/(LG*R(I-1)^2)
2550 RR=2*RA
2560 R(I)=R(I-1)+RR*R(I-1)
2570 US(I)=US(I-1)+RA*US(I-1)
2575 IF PU=0 THEN 2630
2580 PRINT
2590 PRINT KD(I),DS;RA;RR;US(I);R(I)
2600 PRINT A;C0;S,D;LG
2610 PRINT
2615 IF PU=0 THEN 2630
2620 PRINT KD(I),L0,I
2630 NEXT I
2632 IF II=WP THEN 2640
2635 UP(II+1,MM)=US(150)
2636 RP(II+1,MM)=R(150)
2640 MU(MM)=(US(150)-UP(0,MM))/UP(0,MM)
2650 MR(MM)=(R(105)-RP(0,MM))/RP(0,MM)
2652 SU(MM)=MU(MM)
2654 SR(MM)=MR(MM)
2655 TU(II,MM)=MU(MM)
2656 TR(II,MM)=MR(MM)
2660 NEXT MM
2665 WAIT 1500
2700 SU=(SU-(MIN(SU)))/(MAX(SU)-MIN(SU))
2710 SR=(SR-(MIN(SR)))/(MAX(SR)-MIN(SR))
2720 PAGE
2724 IF II=WP THEN 2730
2725 IF ZA=0 THEN 2800
2730 PRINT "MAX DUTS/UTS= ",MAX(MU)
2740 PRINT "MIN DUTS/UTS= ",MIN(MU)
```

```
2750 WINDOW -BH,TH,0,1
2760 VIEWPORT 250,750,100,600
2770 SETGR TICS 5,5,GRAT 5,5
2780 XYPLOT YY,SU
2790 PRINT "^[^W^[^L"
2800 NEXT II
2803 PAGE
2810 PRINT "DTS/UTS FOR WP=0,3"
2812 PRINT "E","D","C","B","A"
2814 FOR QQ=0 TO WP
2816 PRINT TU(QQ,0),TU(QQ,1),TU(QQ,2),TU(QQ,3),TU(QQ,4)
2818 PRINT
2820 NEXT QQ
2840 PRINT "DR/R FOR WP=0,3"
2842 PRINT "E","D","C","B","A"
2844 FOR QQ=0 TO WP
2846 PRINT TR(QQ,0),TR(QQ,1),TR(QQ,2),TR(QQ,3),TR(QQ,4)
2848 PRINT
2850 NEXT QQ
2855 WAIT 1500
2860 PRINT "^[^W^[^L"
2865 WAIT 1500
2900 STOP
2910 END
3000 REM *** COMPUTATION OF HAZ TEMPERATURE HISTORY ***
3005 IF II=0 THEN 3009
3006 IF MM=LU THEN 3009
3007 F1=NC
3008 GOTO 3010
3009 F1=CC
3010 P1=P0*(1-F1/100)
3015 PRINT II,MM,LU,F1
3020 P2=P1*(1-F2/100)
3030 P1=P1-P2
3040 LET N=150
3050 DIM XX(N),TA(N),TE(N)
3060 LET TE=LT
3070 FOR I=0 TO N
3080 LET XX(I)=XA+(XB-XA)/N*I
3090 NEXT I
3110 FOR I=0 TO N
3120 LET X=XX(I)
3130 GOSUB 3290
3140 LET TA(I)=M2
3145 IF TA(I)>LT THEN LET TA(I)=LT+10
3150 NEXT I
3160 REM *** PRINTOUT OF RESULTS ***
3170 PAGE
3175 IF ZA=0 THEN 3280
3180 PRINT "WELD TEMPERATURE PROFILE:";Y;"INCHES FROM CENTERLINE."
3190 PRINT "PROFILES TAKEN AT ",Z/W1*100;" % PLATE DEPTH."
3200 FOR I=0 TO 10\PRINT\NEXT I
3210 PRINT " TEMP"\PRINT\PRINT
3220 PRINT "(DEG F)"
3230 FOR I=0 TO 16\PRINT\NEXT I
3240 PRINT "                    DISTANCE FROM HEAT SOURCE (INCHES)";
3250 WINDOW XA,XB,0,TG
3260 SETGR WINDOW,TICS 5,10,5,5,GRAT 6,6,3,3
3270 XYPLOT XX,TA
3275 PRINT "^[^W^[^L"
3280 RETURN
3290 REM *** SUBROUTINE TO COMPUTE TEMPERATURE OF HEAT SOURCE ARRAY ***
3300 LET Z2=Z
3310 LET M2=0
3320 LET D3=0
3330 LET D2=2*W1
3340 GOSUB 3650
3350 GOSUB 3510
3360 LET M2=M1+T0+T2
3370 LET M3=M2
```

```
3380 LET D3=D3+D2
3390 GOSUB 3430
3400 IF (M2-M3)<.01*M2 THEN GOTO 3420
3410 GOTO 3370
3420 RETURN
3430 REM *** SUBROUTINE TO ADD NEXT TWO HEAT SOURCES ***
3440 LET Z2=D3+Z
3450 GOSUB 3650
3460 LET M2=M2+M1
3470 LET Z2=D3-Z
3480 GOSUB 3650
3490 LET M2=M2+M1
3500 RETURN
3510 REM *** SUBROUTINE TO COMPUTE LINE HEAT SOURCE TEMPERATURE
3520 REM DISTRIBUTION ***
3530 LET K0=0
3540 LET T2=0
3550 LET AR=V1/2/A1*X
3560 LET Z3=V1/2/A1*SQR(X*X+Y*Y)
3570 IF AR>88 THEN 3640
3580 GOSUB 3730
3590 IF AR<0 THEN 3620
3600 LET T2=P2/W1/6.2832/K1/EXP(AR)*K0
3610 GOTO 3640
3620 LET AR=-AR
3630 LET T2=P2/W1/6.2832/K1*EXP(AR)*K0
3640 RETURN
3650 REM *** SUBROUTINE TO COMPUTE TEMPERATURE ***
3660 LET S1=SQR(X*X+Y*Y+Z2*Z2)
3670 IF S1=0 THEN LET M1=UT+1000\IF S1=0 THEN 3720
3680 LET AR=V1/2/A1*(S1+X)
3690 IF AR>88 THEN LET M1=0
3700 IF AR>88 THEN GOTO 3720
3710 LET M1=P1/2/3.1416/K1/S1/EXP(AR)
3720 RETURN
3730 REM *** MODIFIED BESSEL FUNCTION, SECOND KIND,ZEROTH ORDER ***
3740 REM *** POLYNOMIAL APPROXIMATION ***
3750 IF Z3>2 THEN 3820
3760 GOSUB 3870
3770 LET G2=Z3*Z3/4
3780 LET K0=((7.4E-06*G2+1.075E-04)*G2+2.62698E-03)*G2
3790 LET K0=((K0+.0348859)*G2+ 2306976)*G2
3800 LET K0=((K0+.4227842)*G2-.5772157)-.5*LOG(G2)*I0
3810 GOTO 3860
3820 LET G2=2/Z3
3830 LET K0=((5.3208E-04*G2-2.5154E-03)*G2+5.87872E-03)*G2
3840 LET K0=((K0-.01062446)*G2+.02189568)*G2
3850 LET K0=((K0-.07832358)*G2+1 253314)/SQR(Z3)/EXP(Z3)
3860 RETURN
3870 REM *** MODIFIED BESSEL FUNCTION, FIRST KIND, ZEROTH ORDER ***
3880 REM *** POLYNOMIAL APPROXIMATION ***
3890 IF Z3>3.75 THEN 3950
3900 LET G1=Z3*Z3
3910 LET I0=((5 923979E-10*G1+6.56017E-08)*G1+6.80123E-06)*G1
3920 LET I0=((I0+4.3394E-04)*G1+.0156252)*G1
3930 LET I0=(I0+.25)*G1+1
3940 GOTO 3990
3950 LET I0=((153.445/Z3-171.822)/Z3+73.2919)/Z3
3960 LET I0=((I0-15.2595)/Z3+1.81198)/Z3
3970 LET I0=((I0-.0830909)/Z3+.0316855)/Z3
3980 LET I0=((I0+.0498222)/Z3+.3989423)*EXP(Z3)/SQR(Z3)
3990 RETURN

READY
*
```

```
10 REM *** RAPID DIFFUSSION ANNEALING ***
20 REM *** INCREASE IN ULTIMATE STRENGTH ***
30 CLEAR
35 PRINT "INPUT 1 IF MAX PRINTED OUTPUT WANTED, 0 OTHERWISE."
36 INPUT PU
40 PRINT "THIS PROGRAM CALCULATES INCREASED ULTIMATE"
50 PRINT "STRENGTH DUE TO RAPID DIFFUSION ANNEALING"
52 PRINT "(BLUNTING) OF MICROCRACKS. TEMPERATURES AT"
54 PRINT "A MATERIAL POINT ARE TO BE ENTERED FOR DISCRETE"
56 PRINT "TIMES OR CALCULATED FROM THE ATTACHED SUBROUTINE."
60 PRINT
62 PRINT "INPUT 0 TO SKIP ALL PRINTING EXCEPT THE LAST."
63 PRINT "INPUT 1 TO GET TEMP , POINT DATA, ET. AL."
64 INPUT ZA
70 PRINT "ENTER 0 IF THE SUBROUTINE IS TO BE CALLED."
72 PRINT "ENTER 1 OTHERWISE"
80 INPUT B
81 PRINT "INPUT THE NUMBER OF HEAT PASSES NOT INCLUDING THE WELD PASS."
82 INPUT WP
83 PRINT "INPUT NPTS-1 ACROSS THE DIAGONAL."
84 INPUT LV
85 DELETE UP,RP,TU,TR
86 DIM UP(WP,LV),RP(WP,LV)
87 DIM TU(WP,LV),TR(WP,LV)
88 FOR II=0 TO WP
90 IF B=1 THEN 2030
200 REM *** HAZ TEMPERATURE HISTORY ***
210 REM *** DATA INPUT ***
230 PRINT "PLEASE SELECT THE NUMBER OF THE METAL TO BE WELDED"
240 PRINT "FROM THE LIST BELOW."\PRINT\PRINT\PRINT
250 PRINT "0. UNLISTED METAL"\PRINT
260 PRINT "1. 2219 ALUMINUM"\PRINT
270 PRINT "2. 302 STAINLESS STEEL"\PRINT
280 PRINT "3. 321 STAINLESS STEEL"\PRINT
```

```
290 PRINT "4. INCONEL 718"\PRINT
300 INPUT Q
310 IF Q=1 THEN 550
320 IF Q=2 THEN 570
330 IF Q=3 THEN 590
340 IF Q=4 THEN 610
350 PRINT "WHAT IS THE METAL TO BE WELDED?"\PRINT\PRINT\PRINT
360 INPUT M$
370 PRINT "PLEASE WRITE IN THE LOWER AND UPPER LIMITS OF THE MELTING"
380 PRINT "TEMPERATURE RANGE OF THE ALLOY TO BE WELDED. USE UNITS OF"
390 PRINT "DEGREES FAHRENHEIT. SEPARATE THE TWO VALUES BY A COMMA."
400 PRINT "NOTE: A GOOD SOURCE REFERENCE FOR THIS KIND OF DATA IS THE"
410 PRINT "AEROSPACE STRUCTURAL MATERIALS HANDBOOK."\PRINT\PRINT\PRINT
420 INPUT LT,UT
430 PRINT "WHAT IS THE THERMAL CONDUCTIVITY OF THE ALLOY IN BTU'S PER"
440 PRINT "HOUR PER FOOT PER DEGREE FAHRENHEIT?"\PRINT\PRINT\PRINT
450 INPUT K1
460 LET K1=K1*2.441E-05
470 PRINT "WHAT IS THE SPECIFIC HEAT OF THE ALLOY IN BTU'S PER LB"
480 PRINT "PER DEGREE FAHRENHEIT?"\PRINT\PRINT\PRINT
490 INPUT C1
500 PRINT "WHAT IS THE DENSITY OF THE ALLOY IN LBS PER CUBIC INCH?"
510 PRINT\PRINT\PRINT
520 INPUT RO
530 LET A1=K1/RO/C1*56.83
540 GOTO 630
550 LET UT=1190\LET LT=1010\LET K1=2.44E-03\LET A1=5.56
560 LET M$="2219 ALUMINUM"\GOTO 630
570 LET UT=2650\LET LT=2550\LET K1=4.27E-04\LET A1=.5
580 LET M$="302 STAINLESS STEEL"\GOTO 630
590 LET UT=2550\LET LT=2500\LET K1=4.03E-04\LET A1=.66
600 LET M$="321 STAINLESS STEEL"\GOTO 630
610 LET UT=2437\LET LT=2300\LET K1=3.83E-04\LET A1=.71
620 LET M$="INCONEL 718"\GOTO 630
630 PRINT "THE METAL TO BE WELDED IS NOW CHARACTERIZED. WE NOW"
```

```
640 PRINT "TURN TO THE WELDING PROCESS PARAMETERS."\PRINT\PRINT\PRINT
650 PRINT "WHAT IS THE AMBIENT TEMPERATURE OF THE METAL IN DEGREES"
660 PRINT "FAHRENHEIT? IF THE METAL IS PREHEATED, GIVE THE PREHEAT"
670 PRINT "TEMPERATURE AS THE AMBIENT TEMPERATURE."\PRINT\PRINT\PRINT
680 INPUT T0
760 PRINT "PLEASE SPECIFY WELD POWER IN KILOWATTS."
770 PRINT\PRINT\PRINT
780 INPUT P0
790 PRINT "PLEASE SPECIFY WELD SPEED IN INCHES PER MINUTE."
800 PRINT\PRINT\PRINT
810 INPUT V1
820 PRINT "WHAT PERCENT OF TOTAL BEAM POWER IS LOST FROM THE WELD"
830 PRINT "PUDDLE DUE TO PROCESSES OTHER THAN CONDUCTION BY THE PLATE?"
840 PRINT "THESE LOSSES INCLUDE RADIATION AND METAL EVAPORATION FROM"
850 PRINT "THE VICINITY OF THE PUDDLE."\PRINT\PRINT\PRINT
860 INPUT F1
861 PRINT "INPUT THE NEW NON-CONDUCTIVE PERCENT LOSSES FOR DEEP PTS."
862 INPUT NC
863 CC=F1
870 PRINT "WHAT PERCENT OF THE REMAINING BEAM POWER IS ABSORBED CLOSE"
880 PRINT "TO THE METAL SURFACE SO AS TO FORM THE EB WELD NAILHEAD?"
890 PRINT "THIS WOULD BE THE PERCENTAGE OF THE BEAM CURRENT LACKING"
900 PRINT "SUFFICIENT POWER DENSITY TO VAPORIZE THE METAL."
910 PRINT\PRINT\PRINT
920 INPUT F2
940 DIM KD(150),TS(150),US(150),R(150)
950 IF II<>0 THEN 1140
960 PRINT "PLEASE SELECT LENGTH OBSERVED: 0.5, 2.5, 5, 10, 25 INCHES."
970 PRINT\PRINT\PRINT
980 INPUT %B\LET %B=%B/5\LET %A=-4*%B
990 PRINT "PLEASE SELECT MAXIMUM TEMPERATURE: 1000, 2000, 5000, 10000 DEG
F."
1000 PRINT\PRINT\PRINT
1010 INPUT TG
1020 PRINT "INPUT HALF THE CRACK LENGTH IN CENTIMETERS."
```

```
1030 INPUT L
1040 PRINT "INPUT THE LOWER MELTING TEMPERATURE(DEG. KELVIN)."
1050 INPUT LQ
1060 PRINT "INPUT THE RADIUS OF THE TIP OF THE CRACK(CM)."
1070 INPUT R(0)
1080 REM R IS ASSUMED MUCH LESS THAN L
1090 PRINT "INPUT THE ULTIMATE STRESS."
1100 INPUT US(0)
1102 FOR MM=0 TO LV
1103 UP(0,MM)=US(0)
1104 RP(0,MM)=R(0)
1105 NEXT MM
1106 PRINT\PRINT
1110 PRINT "INPUT ONE HALF THE ROOT WIDTH,ONE HALF THE CROWN WIDTH,"
1112 PRINT "AND THE PLATE THICKNESS(DIMENSIONS IN INCHES)."
1120 INPUT BH,TH,W1
1125 DELETE YY,ZZ,MU,MR,SU,SR
1130 DIM YY(LV),ZZ(LV),MU(LV),MR(LV),SU(LV),SR(LV)
1140 FOR MM=0 TO LV
1145 IF II<>0 THEN US(0)=UP(II,MM)
1146 IF II<>0 THEN R(0)=RP(II,MM)
1150 Y=-BH+(TH+BH)*MM/LV
1160 Z=-W1*(Y-TH)/(BH+TH)
1170 YY(MM)=Y
1180 ZZ(MM)=Z
1190 GOSUB 3000
1200 WAIT 1500
1210 PAGE
2020 GOTO 2130
2030 PRINT "INPUT ONE LESS THAN THE NUMBER OF DISCRETE"
2040 PRINT "TEMPERATURES TO BE CONSIDERED."
2050 INPUT M
2060 DIM KD(M),TS(M)
2070 DIM US(M),R(M)
2080 FOR I=0 TO M
```

```
2090 PRINT "INPUT TEMPERATURE(DEG. KELVIN),TIME(SECONDS)"
2100 INPUT KD(I),TS(I)
2110 NEXT I
2120 GOTO 2220
2130 FOR I=0 TO 150
2140 TA(I)=5*TA(I)/9+255.37
2150 NEXT I
2160 DT=(2*XB)/V1
2170 M=150
2180 FOR I=0 TO 150
2190 KD(I)=TA(150-I)
2200 NEXT I
2290 AL=2*ATN(R(0)/L)
2300 PI=4*ATN(1)
2310 OM=16.48*10^(-24)
2340 PAGE
2341 IF PU=0 THEN 2420
2350 PRINT "Z=";Z;"Y=";Y;"L=";L;"R(0)=";R(0)
2360 PRINT "AL=";AL;"US(0)=";US(0)
2370 PRINT
2380 PRINT "KD(I)        DS       RA       RR       US(I)       R(I)"
2390 PRINT "A            C0       S        D        LG"
2400 PRINT
2410 PRINT
2420 FOR I=1 TO M
2430 IF KD(I)<=LQ THEN 2470
2440 US(I)=UP(0,MM)
2450 R(I)=RP(0,MM)
2452 IF ZA=0 THEN 2460
2455 PRINT II;I;MM;KD(I),R(I-1),US(I-1)
2460 GOTO 2610
2470 IF B=0 THEN LET DS=DT
2480 IF B=1 THEN LET DS=TS(I)-TS(I-1)
2490 A=(OM*(PI-AL)*DS)/(4*(SIN((PI-AL)/2)/COS((PI-AL)/2))-((PI-AL)/2))
2500 C0=6.066*10^(22)*EXP(-8478/KD(I))
```

```
2502 IF ZA=0 THEN 2510
2505 PRINT II;I;MM;KD(I),R(I-1),US(I-1)
2510 S=EXP(1500*OM/(1.381*10^(-16))/R(I-1)/KD(I))-1
2520 D=.176*EXP(-15213/KD(I))
2530 LG=LOG(L/R(I-1))
2540 RA=A*C0*S*D/(LG*R(I-1)^2)
2550 RR=2*RA
2560 R(I)=R(I-1)+RR*R(I-1)
2570 US(I)=US(I-1)+RA*US(I-1)
2575 IF PU=0 THEN 2630
2580 PRINT
2590 PRINT KD(I);DS;RA;RR;US(I);R(I)
2600 PRINT A;C0;S;D;LG
2610 PRINT
2615 IF PU=0 THEN 2630
2620 PRINT KD(I),L0,I
2630 NEXT I
2632 IF II=WP THEN 2640
2635 UP(II+1,MM)=US(150)
2636 RP(II+1,MM)=R(150)
2640 MU(MM)=(US(150)-UP(0,MM))/UP(0,MM)
2650 MR(MM)=(R(105)-RP(0,MM))/RP(0,MM)
2652 SU(MM)=MU(MM)
2654 SR(MM)=MR(MM)
2655 TU(II,MM)=MU(MM)
2656 TR(II,MM)=MR(MM)
2660 NEXT MM
2665 WAIT 1500
2700 SU=(SU-(MIN(SU)))/(MAX(SU)-MIN(SU))
2710 SR=(SR-(MIN(SR)))/(MAX(SR)-MIN(SR))
2720 PAGE
2724 IF II=WP THEN 2730
2725 IF ZA=0 THEN 2800
2730 PRINT "MAX OUTS/UTS= ",MAX(MU)
2740 PRINT "MIN OUTS/UTS= ",MIN(MU)
```

```
2750 WINDOW -BH,TH,0,1
2760 VIEWPORT 250,750,100,600
2770 SETGR TICS 5,5,GRAT 5,5
2780 XYPLOT YY,SU
2790 PRINT "^[^W^[^L"
2800 NEXT II
2809 PAGE
2810 PRINT "DTS/UTS FOR WP=0,3"
2812 PRINT "E","D","C","B","A"
2814 FOR QQ=0 TO WP
2816 PRINT TU(QQ,0),TU(QQ,1),TU(QQ,2),TU(QQ,3),TU(QQ,4)
2818 PRINT
2820 NEXT QQ
2840 PRINT "DR/R FOR WP=0,3"
2842 PRINT "E","D","C","B","A"
2844 FOR QQ=0 TO WP
2846 PRINT TR(QQ,0),TR(QQ,1),TR(QQ,2),TR(QQ,3),TR(QQ,4)
2848 PRINT
2850 NEXT QQ
2855 WAIT 1500
2860 PRINT "^[^W^[^L"
2865 WAIT 1500
2900 STOP
2910 END
3000 REM *** COMPUTATION OF HAZ TEMPERATURE HISTORY ***
3005 IF II=0 THEN 3009
3006 IF MM=LU THEN 3009
3007 F1=NC
3008 GOTO 3010
3009 F1=CC
3010 P1=P0*(1-F1/100)
3015 PRINT II,MM,LU,F1
3020 P2=P1*(1-F2/100)
3030 P1=P1-P2
3040 LET N=150
```

```
3050 DIM XX(N),TA(N),TE(N)
3060 LET TE=LT
3070 FOR I=0 TO N
3080 LET XX(I)=XA+(XB-XA)/N*I
3090 NEXT I
3110 FOR I=0 TO N
3120 LET X=XX(I)
3130 GOSUB 3290
3140 LET TA(I)=M2
3145 IF TA(I)>LT THEN LET TA(I)=LT+10
3150 NEXT I
3160 REM *** PRINTOUT OF RESULTS ***
3170 PAGE
3175 IF ZA=0 THEN 3280
3180 PRINT "WELD TEMPERATURE PROFILE:";Y;"INCHES FROM CENTERLINE."
3190 PRINT "PROFILES TAKEN AT ";Z/W1*100;" % PLATE DEPTH."
3200 FOR I=0 TO 10\PRINT\NEXT I
3210 PRINT " TEMP"\PRINT\PRINT
3220 PRINT "(DEG F)"
3230 FOR I=0 TO 16\PRINT\NEXT I
3240 PRINT "                       DISTANCE FROM HEAT SOURCE (INCHES)";
3250 WINDOW XA,XB,0,TG
3260 SETGR WINDOW,TICS 5,10,5,5,GRAT 6,6,3,3
3270 XYPLOT XX,TA
3275 PRINT "^[^W^[^L"
3280 RETURN
3290 REM *** SUBROUTINE TO COMPUTE TEMPERATURE OF HEAT SOURCE ARRAY ***
3300 LET Z2=Z
3310 LET M2=0
3320 LET D3=0
3330 LET D2=2*W1
3340 GOSUB 3650
3350 GOSUB 3510
3360 LET M2=M1+T0+T2
3370 LET M3=M2
```

```
3380 LET D3=D3+D2
3390 GOSUB 3430
3400 IF (M2-M3)<.01*M2 THEN GOTO 3420
3410 GOTO 3370
3420 RETURN
3430 REM *** SUBROUTINE TO ADD NEXT TWO HEAT SOURCES ***
3440 LET Z2=D3+Z
3450 GOSUB 3650
3460 LET M2=M2+M1
3470 LET Z2=D3-Z
3480 GOSUB 3650
3490 LET M2=M2+M1
3500 RETURN
3510 REM *** SUBROUTINE TO COMPUTE LINE HEAT SOURCE TEMPERATURE
3520 REM DISTRIBUTION ***
3530 LET K0=0
3540 LET T2=0
3550 LET AR=V1/2/A1*X
3560 LET Z3=V1/2/A1*SQR(X*X+Y*Y)
3570 IF AR>88 THEN 3640
3580 GOSUB 3730
3590 IF AR<0 THEN 3620
3600 LET T2=P2/W1/6.2832/K1/EXP(AR)*K0
3610 GOTO 3640
3620 LET AR=-AR
3630 LET T2=P2/W1/6.2832/K1*EXP(AR)*K0
3640 RETURN
3650 REM *** SUBROUTINE TO COMPUTE TEMPERATURE ***
3660 LET S1=SQR(X*X+Y*Y+Z2*Z2)
3670 IF S1=0 THEN LET M1=UT+1000\IF S1=0 THEN 3720
3680 LET AR=V1/2/A1*(S1+X)
3690 IF AR>88 THEN LET M1=0
3700 IF AR>88 THEN GOTO 3720
3710 LET M1=P1/2/3.1416/K1/S1/EXP(AR)
3720 RETURN
```

```
3730 REM *** MODIFIED BESSEL FUNCTION, SECOND KIND,ZEROTH ORDER ***
3740 REM *** POLYNOMIAL APPROXIMATION ***
3750 IF Z3>2 THEN 3820
3760 GOSUB 3870
3770 LET G2=Z3*Z3/4
3780 LET K0=((7.4E-06*G2+1.075E-04)*G2+2.62698E-03)*G2
3790 LET K0=((K0+.0348859)*G2+.2306976)*G2
3800 LET K0=((K0+.4227842)*G2-.5772157)-.5*LOG(G2)*I0
3810 GOTO 3860
3820 LET G2=2/Z3
3830 LET K0=((5.3208E-04*G2-2.5154E-03)*G2+5.87872E-03)*G2
3840 LET K0=((K0-.01062446)*G2+.02189568)*G2
3850 LET K0=((K0-.07832358)*G2+1.253314)/SQR(Z3)/EXP(Z3)
3860 RETURN
3870 REM *** MODIFIED BESSEL FUNCTION, FIRST KIND, ZEROTH ORDER ***
3880 REM *** POLYNOMIAL APPROXIMATION ***
3890 IF Z3>3.75 THEN 3950
3900 LET G1=Z3*Z3
3910 LET I0=((5.923979E-10*G1+6.56017E-08)*G1+6.80123E-06)*G1
3920 LET I0=((I0+4.3394E-04)*G1+.0156252)*G1
3930 LET I0=(I0+.25)*G1+1
3940 GOTO 3990
3950 LET I0=((153.445/Z3-171.822)/Z3+73.2919)/Z3
3960 LET I0=((I0-15.2595)/Z3+1.81198)/Z3
3970 LET I0=((I0-.0830909)/Z3+.0316855)/Z3
3980 LET I0=((I0+.0498222)/Z3+.3989423)*EXP(Z3)/SQR(Z3)
3990 RETURN

READY
*
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