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A MODEL FOR PREDICTING
WELD HARDNESS

by

MOHAMED EL-SHAYEB, B.SC. (MECH. ENG.)

A Thesis

Submitted to the School of Graduate Studies in
partial fulfillment of the requirements for the
degree

Master of Engineering

Faculty of Engineering

Carleton University

Ottawa, Ontario

September 1980

A MODEL FOR PREDICTING
WELD HARDNESS

To my parents

U
The undersigned hereby recommend to the Faculty of Graduate
Studies acceptance of this thesis, submitted by Mohamed El-Shayeb,
B.Sc., in partial fulfillment of the requirements for the degree of
Master of Engineering.

Chairman, Department of Mechanical
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ABSTRACT

A model for predicting the hardness distribution of single pass welded joints is proposed. The method is based on a comparison of calculated weld cooling rates with standard Jominy bar cooling rate-hardness data.

The Rosenthal¹ theory of moving heat sources is used to calculate transient temperature distributions in the vicinity of the weld. From the temperature distribution, cooling rates throughout the weld region are calculated using methods proposed by Meyers, Uyehara and Borman². In particular, the cooling rate at 704°C is extracted since this is the thermal parameter reported in the Jominy end quench data. By comparing the 704°C cooling rate distribution with the cooling rate (704°C) vs hardness of the Jominy end quench data, a weld hardness distribution is obtained.

A computer program is developed for calculating the 704°C cooling rate distribution. To ensure reasonable generality, the program includes both two-dimensional and three-dimensional heat flow. Extensive prompting for weld input information and comments throughout ensure that the program is easily used by others for weld thermal studies.

It is shown that, in most cases, while the 704°C cooling rate varies considerably across the weld and heat-affected regions, the hardness distribution extracted from Jominy data is essentially constant. Hence, in many cases, a single centreline hardness can be applied

to the weld as a whole. A hardness-heat input diagram for predicting weld hardness is proposed as a practical convenience.

Calculated hardnesses are compared with experimental data available from the work of Bibby, Goldak and Burbidge³, and from the hardness values reported by Gvildys⁴. The significance of the Jominy weld model is discussed in the light of these comparisons.

The hardness of the fusion zone and heat affected zone is shown to decrease with increasing preheat temperature, thus offering a novel method of estimating the preheat temperature required to produce a specific weld hardness.

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LIST OF PRINCIPAL SYMBOLS

A	Cross-sectional area perpendicular to heat flow (cm^2)
A, B, C, D and n	Constants
BHN	Brinell hardness number
C	Specific heat ($\text{Cal/g}^\circ\text{C}$)
C_1, C_2, C_3 and C_4	Constants
dT/dr	Temperature gradient in r direction ($^\circ\text{C}$)
dT/dt	The rate of cooling ($^\circ\text{C/sec}$)
dT/dx	Temperature gradient in the x direction ($^\circ\text{C}$)
E_{in}	Energy conducted into the volume
E_{out}	Energy conducted out of the volume
f	An undetermined function
FZ	Fusion zone
h	Plate thickness (cm)
HAZ	Heat-affected zone
I	Welding current (Amperes)
I_0, I_1 and I_n	Zero, first and n-order modified functions of the first kind
J_0, J_1 and J_n	Zero, first and n-order Bessel functions of the first kind
K	Thermal conductivity ($\text{J/sec.cm.}^\circ\text{C}$)
K_0, K_1 and K_n	Zero, first and n-order modified Bessel functions of the second kind
MC	Subscript on the parenthesis to indicate the time rate of change of temperature with respect to moving coordinate system

LIST OF PRINCIPAL SYMBOLS (cont'd)

q	The heat input per unit thickness (J/sec.cm.)
$\dot{q}$	Heat generated in the differential volume (J/sec.cm.)
Q	Heat flow rate (J/sec)
$r(2D)$	Distance between the point under consideration and the two-dimensional heat source, $r = \sqrt{x^2 + y^2}$ (cm)
$r(3D)$	Distance between the point under consideration and the three-dimensional heat source, $r = \sqrt{x^2 + y^2 + z^2}$ (cm)
R	Radius of the point heat source, $R = \sqrt{r^2 + z^2}$ (cm)
R_C	Rockwell C hardness
SC	Subscript on the parenthesis to indicate the time rate of change of temperature with respect to stationary coordinate system
t	Time (sec)
T_o	Preheat temperature ($^{\circ}C$)
$T(r, \xi)$	Calculated temperature at point (r, ξ) ($^{\circ}C$)
TS	Tensile strength (KSI)
TTT	Time-temperature-transformation diagram
v	Welding speed (cm/sec)
V	Welding voltage (volts)
VPN	Vicker pyramid number
x, y and z	Cartesian coordinates
Y_o, Y_1 and Y_n	Zero, first and n-order Bessel functions of the second kind
α	Thermal diffusivity (cm^2/sec)
η	Efficiency of the heat transfer

LIST OF PRINCIPAL SYMBOLS (cont'd)

- ξ Distance measured along the weld centreline in the direction of motion. A positive ξ is a distance along the weld centreline in front of the point heat source. A negative ξ is a distance along the weld centreline behind the point heat source (cm).
- ρ Density (g/cm^3)

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CHAPTER 1

INTRODUCTION1.1 GENERAL

One of the most commonly used mechanical tests for determining the quality of a weld is hardness. There are several reasons for using hardness as an indication of the mechanical properties. In the first place, it is a reasonable indication of the tensile strength of the material in the vicinity of the hardness indentation. Standard conversion tables are widely available for converting from hardness to tensile strength. In the absence of such tables, the following conversions provide an approximate tensile strength⁵:

$$\text{T.S.} \approx 5R_C$$

$$\text{T.S.} \approx 0.5 \text{ (VPN)}$$

$$\text{T.S.} \approx 0.5 \text{ (BHN)}$$

where

T.S. = tensile strength (KSI)

R_C = Rockwell C hardness

VPN = Vicker Pyramid Number

BHN = Brinell Hardness Number.

It is not uncommon to find a wide range of tensile strengths throughout the fusion zone (FZ) and heat-affected-zone (HAZ) of a typical weld (Fig. 1.1). Measuring these rapid changes over the relatively small fusion zone and heat-affected-zone of a weld by conventional

FIG. 1.1. A MICROHARDNESS TRAVERSE ACROSS THE FUSION ZONE OF A G40.8B BUTT WELD⁵ FULL PENETRATION ELECTRON BEAM WELD:
 $V=70\text{KW}$, $I=0.025$ amperes, $v=15$ ipm, $h=3/16$ in. and $T_0=25^\circ\text{C}$.

testing techniques is almost impossible. On the other hand, the hardness test is relatively local and hence measuring the hardness (and by implication, the tensile strength) distribution is possible.

While hardness is primarily a measurement of tensile strength, it is also commonly used as an indication of the cracking sensitivity of the material. In a general way, this is based on the fact that as the tensile strength increases, the plastic capacity of the material decreases, i.e. it becomes less ductile. One of the most commonly applied rules in welding is that the hardness should not be allowed to exceed 350 VPN⁶.

The 350 VPN limit implies a simple relationship between hardness and cracking. However, the formation of cracks during welding is complex. Basically, they are caused when relatively hard, brittle structures such as martensite form in the neighbourhood of the weld as a result of the weld thermal cycle. At the same time, the thermal cycle causes high residual tensile stresses and relatively extensive plastic deformation around the weld. If there is insufficient plastic capacity due to martensite formation, then cracks are likely to form. It is evident that several factors besides weld hardness are likely to have an influence on the cracking sensitivity. The restraint of the section has a major influence, as does the shape of the joint which can provide stress concentration effects around the weld. Then, too, researchers have found that the presence of hydrogen in the material greatly increases the chances of crack formation⁶. Hydrogen is induced into the fusion zone (FZ) and heat-affected-zone (HAZ) during welding, primarily from water vapour in the atmosphere.

A more comprehensive method of dealing with weld cracking is the Baily cracking scheme⁶. This method takes into account section size, shape of joint (stress concentration), and hydrogen level of the welding processes. Hardness levels from 350 VPN to 450 VPN are allowed depending upon the severity of the conditions. Nevertheless, the importance of the weld hardness is still evident in this scheme.

Hardness variations across a weld are the result of the thermal cycle. The fusion zone and heat-affected-zone regions are heated into the austenite region or higher and then cooled as the heat source passes on. These regions are, therefore, inadvertently heat-treated. Schematic time-temperature curves are shown in Fig. 1.3 for the weld positions shown in Fig. 1.2.

In principle, these curves can be superimposed on a time-temperature-transformation diagram to predict microstructures in the neighbourhood of the weld, Fig. 1.4⁷. In practice, however, a time-temperature-transformation diagram applies only to materials that are austenitized just above A_{r3} (the upper critical). On the other hand, weld HAZ time-temperature curves have peak temperatures that range from 724°C (the lower critical) to the melting point. In view of this, only that portion of the weld time-temperature curve below the upper critical is superimposed on the T-T-T curve, i.e. the weld cooling curves are all set to time = 0.0 at the upper critical temperature⁷.

The preceding arguments would suggest that weld microstructures can be predicted if the thermal history of points in the neighbourhood of a weld can be calculated from the input welding parameters. Goldak, Bibby and Burbidge⁷, in a recent publication, applied this method to weldments in eutectoid steels with reasonable success.

FIG. 1.2. SELECTED WELD POSITIONS.

FIG. 1.3. SCHEMATIC TIME-TEMPERATURE CURVES FOR SELECTED WELD POSITIONS.

FIG. 1.4. COOLING CURVES SUPERIMPOSED ON TTT SCHEMATIC⁷.

FIG. 1.5. JOMINY END QUENCH TEST⁷.

While microstructure predictions are useful, they provide only a qualitative measurement of mechanical properties. A method of extending this approach to predict the hardness distribution across a weld is suggested in this thesis. This is based on a comparison of 704°C cooling rates calculated for a weld and the 704°C cooling rate-hardness data extracted from Jominy-end quench test results.

The Jominy-end quench test is an established method of determining the hardenability of a material. Essentially, a round bar (usually a 0.75 inch diameter) is heated into the austenite and then cooled from one end with a water jet (Fig. 1.5). The front end of the bar is effectively quenched and reaches a high (martensite) hardness. The cooling rate decreases as the distance from the quenched end increases. The hardness falls as less hard microstructures appear at the slower cooling rates. A hardness traverse along the bar is measured as shown in Fig. 1.5.

In principle, Jominy bar microstructures can be predicted by applying the cooling curve of points along the bar to the T-T-T diagram (Fig. 1.5). This, however, is the same way that a microstructure is predicted for a weld. Therefore, the same microstructure should be found for a point in the vicinity of a weld and a point along a Jominy bar where the cooling curves are the same. This implies that these two points should have the same hardness.

In view of the above arguments, it is evident that the hardness distribution of a weld can be predicted by comparing calculated weld cooling curves with the Jominy cooling curves. The cooling character-

istics of a Jominy test specimen are reported in terms of the cooling rate at 704°C . In fact, the 704°C cooling rate distribution normally associated with standard Jominy data is based on experimentally measured values and varies little with the type or grade of steel if the total alloying content is less than 5 W/O⁶. Because the Jominy thermal history is characterized by the 704°C cooling rate, weld hardnesses are predicted by comparing this with the 704°C cooling rate distribution calculated for a weld. Matching 704°C cooling rates (weld and Jominy test) does not necessarily ensure that the entire cooling curves correspond. However, the structure and hence hardness is, in most cases, determined by cooling changes in the range from about 800°C to 500°C . It is hypothesized, therefore, that matching 704°C cooling rates to predict hardness is justified. However, this can only be confirmed by experiment. This is the aim of this thesis. Hardness distributions are to be calculated for a series of steels and welding conditions. These are then to be compared to experimentally measured values to evaluate the credibility of the proposed method. In addition, the use of this method for calculating preheat values for hardenable steels is investigated.

1.2 OBJECTIVES OF THE PRESENT WORK

The principle objective of this thesis is to examine the applicability of the Jominy-welding model for predicting the hardness distribution in the vicinity of a weld.

The first step in this process involves calculating the cooling rate distribution (Chapter 2) from the theory of moving heat sources of Rosenthal¹ and from further cooling rate relationships established by Meyers et al².

A computer program is submitted (Chapter 3) to provide easily calculated cooling rates for those who may wish to use this technique. The program is provided with an elaborate input "prompt" arrangement and liberal comment statements to facilitate easy use in practice.

The cooling rate distribution across typical low heat, medium heat and higher heat welds is examined in Chapter 4. Hardness distributions across welds for low heat, medium heat and higher heat input are predicted in Chapter 5. A convenient Jominy diagram modified for predicting weld hardness and based on heat input is also proposed in Chapter 5.

The effect of preheat temperature on the hardness of the fusion zone and the heat-affected zone is examined in Chapter 6. The object is to find a method of predicting suitable preheat temperatures for a given hardness.

To investigate the accuracy of the predicted hardness, a comparison with available experimental data has been done in Chapter 7.

CHAPTER 2

HEAT TRANSFER THEORY2.1 INTRODUCTION

As discussed in Chapter 1, the first step in predicting the hardness distribution of a weld is to calculate the 704°C cooling rate distribution from the input welding parameters. This is accomplished with the help of the Rosenthal theory of moving heat sources, and the cooling rate relationships suggested by Meyers et al². These are reviewed and modified for this investigation in this chapter.

2.2 HEAT SOURCES AND HEAT INPUT

To calculate the temperature distribution and the cooling rate of a weld, the amount of heat input from the heat source must be known. There are two essentially different types of heat sources used in welding, the line heat source (penetrating heat source) and the point heat source (surface heat source). A line heat source develops heat with such intensity that it evaporates or otherwise removes metal below the point of application, and thus penetrates the workpiece. The laser and the electron-beam technique when operated at sufficiently high voltage, are penetrating sources (Fig. 2.1). A point source produces heat over a relatively small area of the metal surface, and is shallow penetrating compared to a line source. While a moving line source generates an area, a moving point source generates a line. An example of this type is manual arc welding (Fig. 2.2).

FIG. 2.1. LINE HEAT SOURCE.

FIG. 2.2. POINT HEAT SOURCE.

2.3 THE HEAT INPUT

The amount of heat input transferred to the workpiece is:

$$Q = \eta VI \quad (2.1)$$

where

Q = heat flow rate (Joules/sec)

η = the efficiency of heat transferred

V = the welding voltage (volts)

I = the welding current (amperes).

The efficiency, η , is the percentage of the total energy from the welding machine, transferred to the workpiece. The type of joint, the machine, welder skill, etc. can influence the value of η .

2.3.1 The Heat Input for a Line Source

In the case of a line heat source, the heat input is modified to accommodate the plate thickness h . The heat input per unit thickness (q) is:

$$q = \frac{Q}{h} \text{ Joules/sec-cm} \quad (2.2)$$

or

$$q = \frac{Q}{4.1819h} \text{ Calories/sec-cm} \quad (2.3)$$

A further modification to the heat input is often used in practice. If Eqn. (2.2) is divided by velocity then a parameter is generated that is the heat input per unit of area along the weld centreline. Goldak et al⁷ have shown that this is a unique quantity for

two-dimensional heat flow. Expressed mathematically, this parameter is as follows:

$$q = \frac{Q}{hv} \text{ Joules/cm}^2 \quad (2.4)$$

where

v = welding speed (cm/sec).

2.3.2 The Heat Input for a Point Source

The heat input, Eqn. (2.1), is modified for point sources in a similar way. In this case, however, the unique quantity is the heat input per unit length, i.e.

$$q = \frac{Q}{v} \text{ Joules/cm} \quad (2.5)$$

where

v = welding speed (cm/sec).

2.3.3 Welding Efficiency

The efficiency η can be defined in terms of the net heat rate Q , and the volt-ampere energy rate (VI) of the source from Eqn. (2.1) as:

$$\eta = \frac{Q}{VI}$$

Measurements of the net energy input (Q) and the arc power (VI) have been made for various processes, materials and welding procedures by Christensen⁸. The net heat input is determined by placing the work-piece in a water bath calorimeter. Christensen's results are shown

in Fig. 2.3. They have been used by several subsequent investigators for heat flow studies.

For the welding efficiency, considered in this thesis, an efficiency of $\eta=0.85$ will be used, based upon the recommendation of Goldak et al⁷.

2.3.4 The Heat Flow

These two types of heat sources give rise to two types of heat flow. Two-dimensional heat flow is represented by a line heat source penetrating through a plate of thickness h (Fig. 2.1). Heat flows only in the two directions x and y .

The other type of heat flow is the three-dimensional case, which is represented by a point heat source moving along the top of a thick plate (Fig. 2.2). In this case, heat flows in the three directions x , y and z .

2.4 HEAT TRANSFER THEORY

In most welding processes, heat flow in the workpiece takes place mainly by conduction. The flow of heat is determined by the gradient or difference in temperature levels between two points. Energy is transferred from the high temperature region to the low temperature in the form of heat.

Heat flow is described mathematically by Fourier's law of heat conduction⁹.

$$Q = - KA \frac{dT}{dx} \quad (2.6)$$

FIG. 2.3. ARC WELDING EFFICIENCIES⁸.

where

Q = heat flow rate (cal/sec)

K = thermal conductivity (cal/cm-sec-°C)

A = cross-sectional area perpendicular to heat flow (cm²)

$\frac{dT}{dx}$ = temperature gradient in the direction of the heat flow (°C)

A minus sign means the heat must flow downhill on the temperature scale.

Summation of energy gain and loss in a small volume results in a differential equation which can be used to describe heat flow.

Fig. 2.4 shows a differential volume which has the following energy balance: energy conducted into the volume + heat generated within the volume = change in internal energy + energy conducted out of the volume.

If these quantities are written in differential form and the material properties are considered constants, the following general relationship for three-dimensional heat flow is generated:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{K} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (2.7)$$

where

$\dot{q}$ = heat generated in the differential volume

x, y, z = Cartesian coordinates

$\alpha = \frac{K}{\rho c}$ = the thermal diffusivity of the material (m²/sec or cm²/sec)

where

E_{in} = Energy conducted into the volume

E_{out} = Energy conducted out of the volume

FIG. 2.4. ENERGY BALANCE FOR A DIFFERENTIAL VOLUME.

K = thermal conductivity (cal/cm-sec- $^{\circ}\text{C}$)

ρc = thermal heat capacity ($\text{J/m}^3\text{-}^{\circ}\text{C}$ or $\text{cal/cm}^3\text{-}^{\circ}\text{C}$)

The thermal conductivity (K) is defined as a measure of the energy transfer rate of the material. The higher the thermal conductivity, the greater the heat flow in a material.

The thermal diffusivity (α) of a material is defined as a physical constant that indicates the rate at which heat diffuses through a material. The larger the value of α the faster the heat diffuses through the material. This may be seen by examining the quantities which make up α :

$$\alpha = \frac{K}{\rho c} \quad (2.8)$$

A high value of α results either from a high value of thermal conductivity (K) which indicates a rapid energy-transfer rate, or from a low value of the thermal capacity (ρc). A low value of the heat capacity means that less of the energy moving through the material is absorbed and used to raise the temperature of the material; thus, more energy is available for further transfer.

The values of the thermal conductivity K and thermal capacity ρc are known to vary with both temperature and phase changes in steel. Figs. 2.5 and 2.6 show the temperature dependence of K (thermal conductivity), C (heat capacity)¹⁰.

In the following analysis, average values for K and α are used rather than a particular value for each temperature. Gray et al⁶

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FIG. 2.5. VARIATION OF THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF STEEL WITH TEMPERATURE¹⁰.

FIG. 2.6. THE VARIATION OF THE SPECIFIC HEAT OF STEEL WITH TEMPERATURE.¹⁰

have found that the thermal properties should be evaluated at about one-third of the melting point for most materials. From the results of Gray et al⁶, it can be seen that the values of the thermal conductivity and thermal diffusivity of carbon steel at one-third the melting point (about 1500°C) is:

$$K = 0.1 \text{ cal/cm-sec-}^{\circ}\text{C}$$

$$\alpha = 0.065 \text{ cm}^2/\text{sec}$$

Eqn. (2.7) is a fundamental equation for the heat transfer in materials. The heat generated internally within an element is equal to zero and therefore the final differential equation for three-dimensional heat flow becomes:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (2.9)$$

Eqn. (2.9) is defined in terms of stationary coordinates. However, during welding, the heat source may be stationary (e.g. spot welding) or moving (e.g. arc or electron beam welding). For moving heat sources, a moving coordinate system is found to be an advantage for calculation purposes. In general, two different sets of coordinates are used, one set which is stationary with respect to the earth and one set which is stationary with respect to the heat source. The first set can be referred to as stationary coordinates and the familiar symbols x , y and z are used. The second set can be called moving coordinates and the symbols ξ , η and ζ are used. In view of this, Eqn. (2.9) must be transferred from the stationary coordinates to the moving coordinates (Fig. 2.7).

FIG. 2.7. STATIONARY AND MOVING COORDINATE SYSTEMS.

FIG. 2.8. STEADY-STATE TEMPERATURE ISOTHERMS.

2.4.1 The Heat Transfer Equation in Terms of Moving Coordinates

In the case of moving coordinates, the symbols ξ , y and z are used. The new coordinate ξ is defined as:

$$\xi = x - vt \quad (2.10)$$

where

v = the constant speed of the welding heat source (cm/sec)

ξ = distance from any point to the heat source along the x axis
(Fig. 2.7) (cm)

Note: At the heat source, ξ is always zero because the product vt is always equal to x at this point.

To transform from the stationary to the moving coordinate system, it must be assumed that:

$$T = f(\xi, t)$$

or alternatively the rate of change of temperature can be expressed in either system by the transformation:

$$\left(\frac{\partial T}{\partial t}\right)_{SC} = \left(\frac{\partial T}{\partial t}\right)_{MC} + \frac{\partial T}{\partial \xi} \cdot \frac{\partial \xi}{\partial t} \quad (2.11)$$

where

SC, MC = subscripts on the parentheses to indicate the time rate of change of temperature with respect to either the stationary or moving coordinate systems.

Differentiating Eqn. (2.10) with respect to time and substituting this into Eqn. (2.11) gives:

$$\left(\frac{\partial T}{\partial t}\right)_{SC} = \left(\frac{\partial T}{\partial t}\right)_{MC} - v \frac{\partial T}{\partial \xi} \quad (2.12)$$

Also, from Eqn. (2.10), it can be seen that:

$$\frac{\partial \xi}{\partial x} = 1$$

and

$$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial \xi} \cdot \frac{\partial \xi}{\partial x}$$

i.e.,

$$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial \xi}$$

Therefore,

$$\frac{\partial^2 T}{\partial x^2} = \frac{\partial^2 T}{\partial \xi^2} \quad (2.13)$$

By substituting Eqns. (2.12) and (2.13) into Eqn. (2.9) and by noting that the temperature change with respect to time for moving coordinates $\left(\frac{\partial T}{\partial t}\right)_{MC} = 0$, gives the final differential equation for three-dimensional heat flow with respect to a moving coordinate system:

$$\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = - \frac{v}{\alpha} \frac{\partial T}{\partial \xi} \quad (2.14)$$

Both cases, the stationary and moving coordinates are shown in Fig. 2.7. The continuous moving source is considered to be a process where current, voltage and travel speed are constant. After transient effects have died out, the welding process becomes a steady state operation described as quasi-stationary¹¹. An observer moving with the

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heat source would not be able to detect any temperature change, or in other words, the temperature distribution around the heat source remains constant. The isotherms established around the heat source maintain a constant relationship to one another as they travel along the workpiece with the heat source. A typical example of this temperature distribution is shown in Fig. 2.8.

Eqn. (2.14) is also known as a differential equation of the quasi-stationary state. The cooling rate distribution of a weld can be found by using either the finite difference or the finite element numerical methods to solve Eqn. (2.14). However, these methods can be much more involved albeit more precise than the Rosenthal solution. In view of this, the Rosenthal analytical method is used to solve Eqn. (2.14) in this thesis.

Hardness values are found subsequently by comparing the 704°C cooling rates calculated from the Rosenthal solution to the 704°C cooling rate hardness data of the Jominy-end quench data.

The Rosenthal¹ theory of moving heat sources for both the two- and three-dimensional cases generates the quasi-stationary temperature distribution in the vicinity of the weld. From the temperature distribution, cooling rates for the weld are calculated using a method proposed by Meyers et al². The details of Rosenthal's and Meyer's theories for both two- and three-dimensional cases are not readily available. In view of this, a description of both the Rosenthal¹ and Meyers² theories are contained in the following.

2.4.2 Two-Dimensional Case (Moving Line Source)

Fig. 2.9 shows this situation where the plate is assumed to be infinite in ξ and y directions and has a thickness h in the z direction. The heat source is considered to be a penetrating source or line source of length h . The temperature isotherms are shown in Fig. 2.9. Isotherms of constant temperature are the same throughout the thickness of the plate, since it is assumed there is no temperature gradient in the z direction. In the cross-section AA, it can be seen that the isotherms are vertical lines.

In this case, the heat flows in two directions, one of which is the x or ξ direction. The other direction is taken along the y -axis, and it is assumed that there is no heat flow in the z -direction, thus:

$$\frac{\partial T}{\partial z} = 0$$

In this case, Eqn. (2.14) becomes:

$$\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} = \frac{v}{\alpha} \frac{\partial T}{\partial \xi} \quad (2.15)$$

The general solution for Eqn. (2.15) is of the form:

$$T = e^{-(v/2\alpha)\xi} f(\xi, y) \quad (2.16)$$

where f is an undetermined function.

Differentiating Eqn. (2.16) with respect to ξ and y and substituting in Eqn. (2.15) results in the following:

$$\frac{\partial^2 f}{\partial \xi^2} + \frac{\partial^2 f}{\partial y^2} - \left(\frac{v}{2\alpha}\right)^2 f = 0 \quad (2.17)$$

FIG. 2.9. PHYSICAL SITUATION FOR TEMPERATURE DISTRIBUTIONS IN A THIN PLATE; TWO-DIMENSIONAL CASE, MOVING LINE SOURCE.

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It is convenient to work in cylindrical coordinates with $f(r, \phi)$ where

$$r^2 = \xi^2 + y^2$$

$$\phi = \tan^{-1}(y/\xi)$$

The transformation of Eqn. (2.17) becomes:

$$\frac{\partial^2 f}{\partial r^2} + \frac{1}{r} \frac{\partial f}{\partial r} + \frac{1}{r^2} \frac{\partial^2 f}{\partial \phi^2} - \left(\frac{v}{2\alpha}\right)^2 f = 0$$

According to Rosenthal¹, the function $f(\xi, y)$ is symmetrical about the heat source and, therefore, depends only upon r . In view of this equation (2.18) reduces to the following form:

$$\frac{d^2 f}{dr^2} + \frac{1}{r} \frac{df}{dr} - \left(\frac{v}{2\alpha}\right)^2 f = 0 \quad (2.18)$$

The differential equation (2.16) is recognized as a Bessel form. The general solution of the above equation can be obtained by comparing it with the following generalized Bessel equation developed by Douglass*.

$$x^2 \frac{d^2 y}{dx^2} + \left[(1-2A)x - 2Bx^2 \right] \frac{dy}{dx} + \left[C^2 D^2 x^{2C} + B^2 x^2 - B(1-2A)x + A^2 - C^2 n^2 \right] y = 0 \quad (2.19)$$

Multiplying Eqn. (2.18) by r^2 gives:

$$r^2 \frac{d^2 f}{dr^2} + r \frac{df}{dr} - \left(\frac{v}{2\alpha}\right)^2 r^2 f = 0 \quad (2.20)$$

By comparing Eqn. (2.19) with Eqn. (2.20), Eqn. (2.19) can be written in the following form¹¹:

* Note: while the temperature field (Equation 2.16) is not symmetrical about the heat source, the function $f(\xi, y)$ can take on a symmetrical form.

$$r^2 \frac{d^2 f}{dr^2} + \left[(1-2A)r - 2Br^2 \right] \frac{df}{dr} + \left[C^2 D^2 r^{2C} + B^2 r^2 - B(1-2A)r + A^2 - C^2 n^2 \right] f = 0 \quad (2.21)$$

The generalized solution of Eqn. (2.21) is given by Douglass as:

$$y = x^A e^{Bx} \left[C_1 J_n(Dx^C) + C_2 Y_n(Dx^C) \right] \quad (2.22)$$

The constants A, B, C, D and n can be obtained by equating the corresponding coefficients of Eqns. (2.20) and (2.21) which gives

$$A = 0$$

$$B = 0$$

$$C = 1$$

$$D = i \left(\frac{\nu}{2\alpha} \right)$$

$$n = 0$$

where i is the imaginary argument

Substituting these values of the above constants into Eqn. (2.22)

gives the following equation:

$$f = C_1 J_0 \left(\frac{\nu}{2\alpha} ir \right) + C_2 Y_0 \left(\frac{\nu}{2\alpha} ir \right) \quad (2.23)$$

Substituting Eqn. (2.23) into Eqn. (2.16) gives:

$$T = e^{-(\nu/2\alpha)\xi} \left[C_1 J_0 \left(\frac{\nu}{2\alpha} ir \right) + C_2 Y_0 \left(\frac{\nu}{2\alpha} ir \right) \right] \quad (2.24)$$

The general solution (2.22) requires the use of two new Bessel functions with imaginary arguments corresponding to the substitution of ix for x, i.e. $J_n(ix)$ and $Y_n(ix)$. In the usual notation of $I_n(x)$ and $K_n(x)$, these modified Bessel functions are defined for integer n as:

$$I_n(x) = i^{-n} J_n(ix) \quad (2.25)$$

$$K_n(x) = i^{n+1} \frac{\pi}{2} [J_n(ix) + Y_n(ix)] \quad (2.26)$$

The value of ix corresponds to $(\frac{v}{2\alpha} ir)$ in Eqns. (2.23) and (2.24), hence:

$$x = \frac{v}{2\alpha} r$$

Substituting the values of x and n in both Eqns. (2.25) and (2.26) gives:

$$I_0(\frac{v}{2\alpha} r) = J_0(\frac{v}{2\alpha} ir) \quad (2.27)$$

$$Y_0(\frac{v}{2\alpha} ir) = I_0(\frac{v}{2\alpha} r) - \frac{2}{\pi} K_0(\frac{v}{2\alpha} r) \quad (2.28)$$

Substituting Eqns. (2.27) and (2.28) into Eqn. (2.24) gives the following:

$$T = e^{-(v/2\alpha)\xi} (C_1 + C_2) \left[I_0(\frac{v}{2\alpha} r) \right] - \frac{2}{\pi} C_2 \left[K_0(\frac{v}{2\alpha} r) \right]$$

or

$$T = e^{-(v/2\alpha)\xi} \left[C_3 I_0(\frac{v}{2\alpha} r) + C_4 K_0(\frac{v}{2\alpha} r) \right] \quad (2.29)$$

where

$$C_3 = C_1 + C_2$$

and

$$C_4 = -\frac{2}{\pi} C_2$$

The constants C_3 and C_4 of Eqn. (2.29) are obtained by satisfying the boundary conditions for this case.

2.4.3 Two-Dimensional Boundary Conditions

Referring to Fig. 2.9, consider a circle of radius r drawn around the heat source where $r = \sqrt{\xi^2 + y^2}$. It can be seen that the solution of the heat equation (2.29) depends upon this distance r .

One of the boundary conditions is:

$$\frac{dT}{dr} \rightarrow 0 \quad \text{as } r \rightarrow \infty \quad (2.30)$$

The other boundary condition is obtained from Fourier's law of heat conduction (Eqn. (2.6)) which is:

$$-K(2\pi r) \frac{dT}{dr} \rightarrow q \quad \text{as } r \rightarrow 0 \quad (2.31)$$

where

q = the heat input per unit thickness (Joules/sec-cm)

$2\pi r$ = the circumference of a circle drawn around the heat source
(cm)

Boundary conditions (2.30) and (2.31) must satisfy Eqn. (2.29).

To apply the first boundary condition, Eqn. (2.29) is differentiated with respect to r . This kind of differentiation has the following standard transformation¹²:

$$\frac{d}{dx} I_n'(U) = \left[I_{n-1}(U) - \frac{n}{U} I_n(U) \right] \frac{dU}{dx} \quad (2.32)$$

$$\frac{d}{dx} K_n(U) = \left[-K_{n-1}(U) - \frac{n}{U} K_n(U) \right] \frac{dU}{dx} \quad (2.33)$$

To differentiate the term $C_3 I_0(v/2\alpha r)$ of Eqn. (2.29), Eqn. (2.32) is used. The result of the differentiation is:

$$\frac{d}{dr} I_0\left(\frac{v}{2\alpha} r\right) = I_{-1}\left(\frac{v}{2\alpha} r\right) \cdot \left(\frac{v}{2\alpha}\right) \quad (2.34)$$

Similarly,

$$\frac{d}{dr} K_0\left(\frac{v}{2\alpha} r\right) = -K_{-1}\left(\frac{v}{2\alpha} r\right) \cdot \left(\frac{v}{2\alpha}\right) \quad (2.35)$$

Therefore, the final result of the differentiation for Eqn. (2.29) is:

$$\frac{dT}{dr} = e^{-(v/2\alpha)\xi} \left[C_3 I_{-1}\left(\frac{v}{2\alpha} r\right) \cdot \left(\frac{v}{2\alpha}\right) - C_4 K_{-1}\left(\frac{v}{2\alpha} r\right) \cdot \left(\frac{v}{2\alpha}\right) \right] \quad (2.36)$$

Substituting the first boundary condition which is $\frac{dT}{dr} = 0$ and $r=\infty$ into Eqn. (2.36) gives:

$$C_3 I_{-1}(\infty) - C_4 K_{-1}(\infty) = 0 \quad (2.37)$$

To find the values of I_{-1} and K_{-1} , the following relations can be used¹²:

$$K_{-n}(x) = K_n(x) \quad (2.38)$$

$$I_{-n}(x) = I_n(x) \quad (2.39)$$

Evaluating these functions at infinity provides the following:

$$K_{-1}(\infty) = K_1(\infty) \quad (2.40)$$

$$I_{-1}(\infty) = I_1(\infty) \quad (2.41)$$

Substituting Eqns. (2.40) and (2.41) into Eqn. (2.37) gives:

$$C_3 I_1(\infty) - C_4 K_1(\infty) = 0 \quad (2.42)$$

From Fig. 2.10, it is evident that:

FIG. 2.10. ZERO AND FIRST-ORDER MODIFIED BESSEL FUNCTIONS OF THE FIRST AND SECOND KIND¹¹.

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$$K_1(x) \rightarrow 0 \quad \text{as } x \rightarrow \infty$$

$$I_1(x) \rightarrow \infty \quad \text{as } x \rightarrow \infty$$

Therefore

$$K_1(\infty) = 0 \quad (2.43)$$

$$I_1(\infty) = \infty \quad (2.44)$$

Substituting Eqns. (2.43) and (2.44) into Eqn. (2.42) gives:

$$C_3 = 0$$

Substituting $C_3=0$ into Eqn. (2.29) gives:

$$T = e^{-(v/2\alpha)\xi} C_4 K_0\left(\frac{v}{2\alpha} r\right) \quad (2.45)$$

To apply the second boundary condition, Eqn. (2.31), Eqn. (2.45) has to be differentiated with respect to r :

$$\frac{dT}{dr} = -\frac{v}{2\alpha} e^{-(v/2\alpha)\xi} C_4 K_1\left(\frac{v}{2\alpha} r\right) \quad (2.46)$$

Substituting the value of $\frac{dT}{dr}$ from Eqn. (2.46) into the second boundary condition (Eqn. (2.31)) results in the following:

$$K(2\pi r) \frac{v}{2\alpha} e^{-(v/2\alpha)\xi} C_4 K_1\left(\frac{v}{2\alpha} r\right) = q \quad (2.47)$$

The evaluation at $r=0$ hinges on recalling that the asymptotic approximation to $K_1(x)$ for small x is $1/x$ (Schneider¹¹) so that:

$$K_1\left(\frac{v}{2\alpha} r\right) = \left(\frac{v}{2\alpha} r\right)^{-1} = \frac{2\alpha}{vr} \quad (2.48)$$

Substituting Eqn. (2.48) into Eqn. (2.47) gives:

$$2\pi K C_4 e^{-(v/2\alpha)\xi} = q \quad (2.49)$$

Applying the second boundary condition, Eqn. (2.31) into Eqn. (2.49):

$$C_4 = \frac{q}{2\pi K} \quad (2.50)$$

Substituting the value of the constant C_4 , Eqn. (2.50), into Eqn. (2.45), gives the following heat transfer equation:

$$T(r, \xi) = \frac{q}{2\pi K} e^{-(v/2\alpha)\xi} K_0\left(\frac{v}{2\alpha} r\right) \quad (2.51)$$

where

q is the heat transfer rate of a linear source.

If h is the thickness of the welding piece and Q is the effective welding power: $q = \frac{Q}{h}$. Hence, the final relationship for the heat transfer equation is:

$$T(r, \xi) = T_0 + \frac{Q}{2\pi K h} e^{-(v/2\alpha)\xi} K_0\left(\frac{v}{2\alpha} r\right) \quad (2.52)$$

The temperature $T(r, \xi)$ at any point can be calculated from Eqn. (2.52) if the preheat temperature T_0 , the welding speed v , the welding effective power Q and the thickness of the welding plate h are specified, and if the material parameters K and α are known.

In order to obtain the cooling rates of the weld, Meyers et al.² have differentiated Eqn. (2.52) with respect to time in the fixed coordinate system. This is presented in the following analysis.

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2.4.4 Two-Dimensional Cooling Rates

The cooling rates for a fixed point (x,y) in the plate can be obtained by differentiating Eqn. (2.52) with respect to time.

At a fixed point x,y , x is arbitrarily set equal to zero.

Physically, this means that at time $t=0$, the heat source is at $x=0$, $y=0$ the equation $\xi=x-vt$ becomes $\xi=-vt$. Therefore, the time t at which the heat source passes any point ξ is given by $t=-\xi/v$. Therefore,

$$\xi = -vt \quad (2.53)$$

$$r = \sqrt{\xi^2 + y^2} = \sqrt{v^2 t^2 + y^2} \quad (2.54)$$

Differentiating Eqn. (2.52) with respect to time and substituting Eqns. (2.53) and (2.54) into it:

$$\frac{\partial T}{\partial t} = \frac{Q}{2\pi Kh} \left[e^{v^2 t/2\alpha} \frac{\partial}{\partial t} K_0\left(\frac{v}{2\alpha} \sqrt{v^2 t^2 + y^2}\right) + K_0\left(\frac{v}{2\alpha} \sqrt{v^2 t^2 + y^2}\right) \frac{\partial}{\partial t} e^{v^2 t/2\alpha} \right] \quad (2.55)$$

Note:

$$\frac{\partial}{\partial t} K_0(x) = -K_1(x) \quad (2.56)$$

where $K_1(x)$ is a modified Bessel function of the second kind and first order. By substituting Eqn. (2.56) into Eqn. (2.55), the following relationship for cooling rates is obtained:

$$\frac{dT}{dt} = \frac{Q v^2}{4\pi\alpha Kh} e^{-v\xi/2\alpha} \left[K_0\left(\frac{vr}{2\alpha}\right) + \frac{\xi}{r} K_1\left(\frac{vr}{2\alpha}\right) \right] \quad (2.57)$$

where

$$\frac{dT}{dt} = \text{the rate of cooling at any point } (r,\xi) \text{ } (^{\circ}\text{C})$$

K_1 = modified Bessel function of the second kind and first order.

2.4.5 Two-Dimensional Cooling Rates at the Weld Centreline

According to the theory of Bessel functions¹, Eqn. (2.52) can be reduced to a more simple expression for large values of r :

$$T - T_o = \frac{Q}{2\pi Kh} \frac{e^{-v/2\alpha(\xi+r)}}{\sqrt{vr}} \cdot \sqrt{\alpha\pi} \quad (2.58)$$

Along the weld, $y=0$, $r=|\xi|$ and $\xi=-vt$. Hence, for centreline positions behind the heat source $r=-\xi$ and Eqn. (2.58) becomes¹:

$$T - T_o = \frac{1}{2\sqrt{\pi K C \rho}} \cdot \frac{Q}{vh} \cdot \frac{1}{\sqrt{t}} \quad (2.59)$$

where

$$t = \text{time (sec)}$$

or

$$(T - T_o)\sqrt{t} = C \quad (2.60)$$

By differentiating Eqn. (2.60) with respect to time:

$$\frac{dT}{dt} = -\frac{1}{2} \frac{T - T_o}{t} \quad (2.61)$$

• Substituting the value of the time (t) from Eqn. (2.61) into Eqn. (2.59)

gives:

$$\frac{dT}{dt} = -2\pi K C \rho \left(\frac{vh}{Q}\right)^2 (T - T_o)^3 \quad (2.62)$$

The diffusivity $\alpha = K/\rho C$, hence $\rho C = K/\alpha$.

Substituting the value of ρC into Eqn. (2.62) gives the final equation for the cooling rate at the weld centreline which is:

$$\frac{dT}{dt} = - \frac{2\pi k^2}{\alpha} \left(\frac{vh}{Q}\right)^2 (T-T_o)^3 \quad (2.63)$$

2.4.6 Three-Dimensional Case (Moving Point Source)

Fig. 2.11a shows this situation where the plate is assumed to be infinite in ξ , y and z directions. The figure also shows half of the plate used for typical bead on plate weld situations. If the plate is split in half along plane BB, only half as much heat input is required. In this case, an isotherm in the plate can be imagined as one-half of an egg shell. By looking at the plane BB viewed from the top, it is seen to have an oval shape. By looking at a plane lower than the surface BB, the isotherms are smaller and have a slightly different shape. Also, by looking vertically into the cross-section AA, it shows that the cross-section of the egg shell is circular.

To obtain the temperature distribution for the plate shown in Fig. 2.11a, Rosenthal¹ used the general three-dimensional heat flow Eqn(2.14) as follows:

$$\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{v}{\alpha} \frac{\partial T}{\partial \xi} = 0$$

The general solution for Eqn. (2.14) is:

$$T = e^{-(v/2\alpha)\xi} f(\xi, y, z) \quad (2.64)$$

in which f is an undetermined function.

FIG. 2.11a. PHYSICAL SITUATION FOR TEMPERATURE DISTRIBUTIONS
IN AN INFINITELY THICK PLATE; THREE-DIMENSIONAL
CASE, MOVING POINT SOURCE².

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Differentiating Eqn. (2.64) with respect to ξ , y and z and substituting the results of the differentiation into Eqn. (2.14) results in the following:

$$\frac{\partial^2 f}{\partial \xi^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} - \left(\frac{v}{2\alpha}\right)^2 f = 0 \quad (2.65)$$

To obtain a solution for the three dimensional heat flow situation the same strategy used for solving the two-dimensional case is employed. Equation (2.65) is transformed to polar co-ordinates. Rosenthal¹ shows that $f(\xi, y, z)$ is symmetrical about the heat source and hence angular terms are dropped from the relationship*, i.e.

$$\frac{\partial^2 f}{\partial r^2} + \frac{2}{r} \frac{\partial f}{\partial r} - \left(\frac{v}{2\alpha}\right)^2 f = 0 \quad (2.66)$$

It is easy to see that:

$$\frac{\partial^2 f}{\partial r^2} + \frac{2}{r} \frac{\partial f}{\partial r} = \frac{1}{r} \frac{\partial^2 (rf)}{\partial r^2} \quad (2.67)$$

Substituting Eqn. (2.67) into Eqn. (2.66):

$$\frac{1}{r} \frac{\partial^2 (rf)}{\partial r^2} - \left(\frac{v}{2\alpha}\right)^2 f = 0 \quad (2.68)$$

By multiplying Eqn. (2.68) by r leads to:

$$\frac{\partial^2 (rf)}{\partial r^2} - \left(\frac{v}{2\alpha}\right)^2 rf = 0 \quad (2.69)$$

Eqn. (2.69) is similar to the familiar differential equation:

$$\frac{\partial^2 T}{\partial x^2} - N^2 T = 0 \quad (2.70)$$

whose general solution has the well-known form:

$$T = C_1 e^{Nx} + C_2 e^{-Nx} \quad (2.71)$$

* Note that while the temperature field is not symmetrical about the heat source (Equation 2.64) the function $f(\xi, y, z)$ can take on a symmetrical form.

A comparison between Eqns. (2.69) and (2.70) gives:

$$rf = C_1 e^{(v/2\alpha)r} + C_2 e^{-(v/2\alpha)r} \quad (2.72)$$

Since the plate is infinite in the ξ , y and z directions, there are no heat losses in these directions and the following boundary conditions should be satisfied (Fig. 2.11b).

$$\frac{\partial T}{\partial \xi} \rightarrow 0 \quad \text{as } \xi \rightarrow \pm \infty \quad (2.73)$$

$$\frac{\partial T}{\partial y} \rightarrow 0 \quad \text{as } y \rightarrow \pm \infty \quad (2.74)$$

$$\frac{\partial T}{\partial z} \rightarrow 0 \quad \text{as } z \rightarrow \pm \infty \quad (2.75)$$

By considering a spherical surface $4\pi r^2$ drawn around the heat source with radius r , the fourth boundary condition is found from the Fourier equation which can be expressed as:

$$-\frac{\partial T}{\partial r} (4\pi r^2) K \rightarrow Q \quad \text{as } r \rightarrow 0 \quad (2.76)$$

where

r = the radial distance from the point heat source (Fig. 2.11b)

which is:

$$r = \sqrt{\xi^2 + y^2 + z^2} = \sqrt{\xi^2 + R^2} \quad (\text{cm}) \quad (2.77)$$

Q = effective welding power (cal/sec).

The first derivative of T with respect to ξ can be obtained by differentiating Eqn. (2.64) as follows:

FIG. 2.11b. THREE-DIMENSIONAL CASE (POINT HEAT SOURCE).

$$\frac{\partial T}{\partial \xi} = e^{-(v/2\alpha)\xi} \frac{\partial f}{\partial \xi} - \left(\frac{v}{2\alpha}\right) e^{-(v/2\alpha)\xi} f \quad (2.78)$$

From Eqns. (2.73) and (2.78), the following relationship should be satisfied:

$$\frac{\partial f}{\partial \xi} = f = 0 \quad \text{as } r \rightarrow \infty \quad (2.79)$$

The relationship (2.79) along with Eqn. (2.72) implies that:

$$C_1 = 0$$

and Eqn. (2.72) reduces to:

$$rf = C_2 e^{-(v/2\alpha)r}$$

or

$$f = \frac{C_2 e^{-(v/2\alpha)r}}{r} \quad (2.80)$$

By differentiating Eqn. (2.80) with respect to r and substituting into Eqn. (2.64), the following expression is obtained:

$$\frac{\partial T}{\partial r} = e^{-(v/2\alpha)\xi} C_2 \left[\frac{-r \left(\frac{v}{2\alpha}\right) e^{-(v/2\alpha)r} - e^{-(v/2\alpha)r}}{r^2} \right] \quad (2.81)$$

Substituting Eqn. (2.76) into Eqn. (2.81) and noting that $r \rightarrow 0$ as $\xi \rightarrow 0$, C_2 can be evaluated:

$$C_2 = \frac{Q}{4\pi K} \quad (2.82)$$

Eqns. (2.64), (2.80) and (2.82) are combined to give:

$$T = \frac{Q}{4\pi r K} e^{-(v/2\alpha)(\xi+r)} \quad (2.83)$$

Eqn. (2.83) is valid for the case of an infinite body (Fig. 2.11). For semi-infinite body (bead on plate weld), the above equation takes the form:

$$T = \frac{Q}{2\pi r K} \cdot e^{-(v/2\alpha)(\xi+r)} \quad (2.84)$$

Taking the initial temperature of surrounding room T_0 into consideration, the final form for the temperature distribution equation becomes:

$$T(r, \xi) = T_0 + \frac{Q}{2\pi r K} e^{-(v/2\alpha)(\xi+r)} \quad (2.85)$$

The cooling rates for the three-dimensional case have been derived by Myers et al.². A brief summary for the derivation is presented in the next section.

2.4.7 Three-Dimensional Cooling Rates

If x is arbitrarily set to zero in Fig. 2.14, then:

$$\xi = -vt \quad (2.86)$$

and the value of r becomes:

$$r = \sqrt{v^2 t^2 + y^2 + z^2} = \sqrt{\xi^2 + R^2} \quad (2.87)$$

Differentiating Eqn. (2.85) with respect to time and using Eqns. (2.86) and (2.87), an expression for the rate of cooling at the point (ξ, y, z) may be obtained:

$$\frac{dT}{dt} = \frac{Qv^2}{4\pi K\alpha \sqrt{\xi^2 + R^2}} \left(1 + \frac{\xi}{\sqrt{\xi^2 + R^2}} + \frac{\xi(2\alpha)}{v(\xi^2 + R^2)} \right) e^{-v/2\alpha(\xi + \sqrt{\xi^2 + R^2})} \quad (2.88)$$

2.4.8 Three-Dimensional Cooling Rates at the Weld Centreline

Eqn. (2.88) is the general form for the rate of cooling of the three-dimensional case. To obtain the rate of cooling at the weld centreline, Rosenthal¹ assumed that, if the observation is limited to the surface of the weld, the distance r is simply the distance $|\xi|$ covered by the heat source in a given period of time t . Substituting this into Eqn. (2.88):

$$\frac{dT}{dt} = \frac{-Qv}{2\pi K\xi^2} \quad (2.89)$$

Substituting the value of r by $-\xi$ in Eqn. (2.85), the following expression for ξ can be obtained:

$$\xi = \frac{-Q}{2\pi K(T-T_0)} \quad (2.90)$$

Substituting Eqn. (2.90) into Eqn. (2.89) gives:

$$\frac{dT}{dt} = \frac{-2\pi K v (T-T_0)^2}{Q} \quad (2.91)$$

Analytical Summary

Eqns. (2.52), (2.57), and (2.63) for the two-dimensional case and Eqns. (2.85), (2.88) and (2.91) for the three-dimensional case can be used to obtain the cooling rates at 704°C. However, the use of these equations is limited in the absence of digital computers. Although digital computers perform just the same operations as can be performed by hand, their speed and capacity make it possible to deal with problems whose solutions are not feasible by hand calculation.

A computer program is developed to calculate the cooling rate distributions at 704°C for both the two-dimensional and three-dimensional cases. A description of the computer program used for this purpose is presented in Chapter 3.

CHAPTER 3

COMPUTER MODEL3.1 MODEL NAME

Hardness Prediction of Welds (HPOWL)

3.2 MODEL FUNCTION

The computer model described in this chapter was developed by the author, to obtain the cooling rates within the vicinity of a weld. Comparing the computed cooling rates at 704°C , with the cooling rates of standard Jominy end quench data, a weld hardness distribution can be obtained.

The computer work was approached in the following way for both the two- and three-dimensional cases:

1. Determination of temperature distribution and the rate of cooling at 704°C within the weld fusion zone (FZ) and heat-affected zone (HAZ).
2. Determination of the cooling rate distribution within these same zones.
3. Determination of the cooling rate at the weld centreline.

3.3 PROGRAM DESCRIPTION

Table 3.1 shows the input symbols which are required for running the program. The table also contains the units that must be used to submit the data to the program. Table 3.2 shows the computer program variables together with the units that are contained in the model.

TABLE 3.1. COMPUTER PROGRAM INPUT SYMBOLS.

<u>SYMBOL</u>	<u>NAME AND DESCRIPTION</u>	<u>UNITS</u>
A	I Welding current intensity	amperes
H	h Workpiece thickness (converted to cm)	inches
ITER	ITER Maximum number of iterations	dimensionless
NY	NY Number of divisions on Y axis	dimensionless
NZ	NZ Number of divisions on Z axis	dimensionless
TIR	TIR Time increment required (defined as $t = -\xi/V$)	seconds
TO	T_o Preheat temperature	$^{\circ}\text{C}$
V	v Welding speed converted to cm/sec	inches/min
VT	V Welding voltage	volts
YIR	YIR Increments required on Y axis	cm

TABLE 3.2. COMPUTER PROGRAM VARIABLES.

<u>SYMBOL</u>	<u>NAME AND DESCRIPTION</u>	<u>UNITS</u>
ALFA	α Thermal diffusivity (Eqn. (2.8))	cal/cm-sec-°C
EFF	η Welding efficiency (Eqn. (2.1))	dimensionless
FIO	$I_0(x)$	dimensionless
FI1	$I_1(x)$	
FKO	$K_0(x)$	
FK1	$K_1(x)$	
	Bessel functions of first and second order. See Appendix 1.	
PI	π Defined to equal 3.14159	dimensionless
Q	Q Heat flow rate (Eqn. (2.1))	J/sec
QPC	QPC Heat input per calories	cal/cm-sec
QPUA1	Heat input per unit area (Eqn. (2.4))	J/in ²
QPUA2		J/cm ²
QPUA3		J/mm ²
QPUA4		KJ/in ²
QPUA5		KJ/cm ²
QPUA6		KJ/mm ²
QPUL1	Heat input per unit length (Eqn. (2.5))	J/in
QPUL2		J/cm
QPUL3		J/mm
QPUL4		KJ/in
QPUL5		KJ/cm
QPUL6		KJ/mm
QPUT1	Heat input per unit thickness (Eqn. (2.2))	J/s-in
QPUT2		J/s-cm
R	Radial distance Defined as $R = \sqrt{Y^2 + \xi^2}$ 2-dimensional case or $R = \sqrt{Y^2 + \xi^2 + Z^2}$ 3-dimensional case	cm

TABLE 3.2. (cont'd)

<u>SYMBOL</u>	<u>NAME AND DESCRIPTION</u>	<u>UNITS</u>
ROC	ROC Rate of cooling at point (ξ, Y) Eqns. (2.57) and (2.88)	$^{\circ}\text{C/sec}$
RROC	Radius distance at rate of cooling	cm
S	Number of negative time increments	dimensionless
TEMP	$T(\xi, Y)$ Temperature at point (ξ, Y) Eqns. (2.52) and (2.85)	$^{\circ}\text{C}$
TEMROC	$T(\xi, Y)$ Temperature at rate of cooling	$^{\circ}\text{C}$
TIME	t Time $t = -\xi/V$	sec
TIMROC	t at ROC Time $t = -ZETROC/V$	
TK	K Thermal conductivity (Eqn. (2.8))	cm^2/sec
U	U Radial distance Defined as: $U = \sqrt{R^2 + (ZETA)^2}$	cm
Y	Y Distance from weld centreline in direction of Y axis	cm
YROC	YROC Distance from weld centreline at ROC in direction of Y axis	cm
ZETA	ξ Distance along weld centreline	cm
ZETROC	ZETROC Distance along weld centreline at ROC	cm

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The computer model flow chart is shown in Fig. 3.1 which is used to describe the general development of the program in the following discussion.

3.3.1 The Master Program

The master program leads to six subroutines by asking the user six questions indicated within the diamond figures A, B, C, D, E and F in Fig. 3.1. The user has the option of selecting all or some of the subroutines by answering these questions by a "yes" or "no" decision. If the user's answer to the first question (diamond Fig. A) is "yes", the master program transfers to subroutine 1 which start by asking the user for the input data required to make the first calculation. The first subroutine then proceeds to calculate the two-dimensional quasi-stationary temperature distribution and the cooling rate distribution. If the user's answer to the first question is no, the master program leads directly to the next question (diamond Fig. B) and once again the user is asked for a "yes" or "no" decision. If the decision is "yes", the second subroutine is activated. If the answer is "no", the master program proceeds to the third subroutine and so on as shown within the diamond Figs. C, D, E and F. After completing the last question (diamond F), the master program is followed by a STOP.

3.3.2 The First Subroutine TD2D and ROC704

This subroutine calculates the temperature distribution of the two-dimensional case TD2D, and the rate of cooling at 704°C ROC704 distribution across the weld. The detailed subroutine is shown in Fig. 3.2.

FIG. 3.1. OUTLINE FLOW CHART OF THE MASTER PROGRAM.

FIG. 3.2. OUTLINE FLOW CHART OF THE FIRST SUBROUTINE.

* See Appendix 1.

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FIG. 3.2. (cont'd)

FIG. 3.2. (cont'd)

FIG. 3.2. (cont'd)

Once the user submits the input data, the computer program begins by calculating the heat input (QPC) and the radius R at position 2. In order to calculate the Bessel functions K_0 and I_0 , the value $x = \sqrt{vR}/2\alpha$ must be checked at 4. Depending upon the decision at 4, the Bessel functions are calculated either at 5 and 6 ($x < 2.0$) or at 7 and 8 ($x > 2.0$). Substituting all the calculated values from 3 to 8 into Rosenthal's equation (2.52), a temperature $T(\xi, y)$ is computed at 9 and written at 10. The computer then returns to calculate the rest of the temperature distribution matrix.

3.3.3 Half Interval Method of Determining the 704°C Coordinate Position

In order to find the cooling rate distribution at 704°C, from the Meyers formulation, Eqn. (2.57), it is necessary to locate the 704°C isotherm position (ξ, y) within the temperature distribution matrix. This is carried out by using the so-called "half interval method". This method¹³ is indicated in Fig. 3.2, from 11 to 34 and a summary description of this technique is contained in Appendix 2.

Once the 704°C quasi-stationary positions have been determined, the computer program starts to calculate the cooling rate distribution by using Eqn. (2.57) at 35. It then enters the "Do Loop" for a new calculation until all the 704°C cooling rates across the weld are calculated. The results are written at 37 and the process stops at 38.

3.3.4 The Second Subroutine ROC2D

This subroutine calculates the rate of cooling of the two-dimensional case ROC2D. Details of the subroutine are shown in Fig. 3.3, Steps 1 to 10.

FIG. 3.3. OUTLINE FLOW CHART OF THE SECOND SUBROUTINE.

3.3.5 The Third Subroutine RWCL2D

This subroutine calculates the rate of cooling at the weld centreline of the two-dimensional case RWCL2D. Details of the subroutine are shown in Fig. 3.4, Steps 1 to 4.

3.3.6 The Fourth Subroutine TD3D and ROC704

This subroutine calculates the temperature distribution of the three-dimensional case TD3D and the rate of cooling at 704°C ROC704.

Details of the subroutine are shown in Fig. 3.5, Steps 1 to 24.

3.3.7 The Fifth Subroutine ROC3D

This subroutine calculates the rate of cooling of the three-dimensional case ROC3D. Details of the subroutine are shown in Fig. 3.6, Steps 1 to 4.

3.3.8 The Sixth Subroutine RWCL3D

This subroutine calculates the rate of cooling at the weld centreline of the three-dimensional case RWCL3D. Details of the subroutine are shown in Fig. 3.7, Steps 1 to 4.

3.4 SAMPLE READOUT

3.4.1 The Input Data and the Welding Parameters

Once the program is activated, the master program asks the user the first question as shown in Fig. 3.8a. If the answer is "yes", the program asks for the welding parameters, one at a time. Each request

FIG. 3.4. OUTLINE FLOW CHART OF THE THIRD SUBROUTINE.

FIG. 3.5. OUTLINE FLOW CHART OF THE FOURTH SUBROUTINE.

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FIG. 3.5. (cont'd)

FIG. 3.5. (cont'd)

FIG. 3.5. (cont'd)

FIG. 3.8. OUTLINE FLOW CHART OF THE FIFTH SUBROUTINE.

FIG. 3.7. OUTLINE FLOW CHART OF THE SIXTH SUBROUTINE.

```

!HPOWL1
DO YOU WANT TD2D & ROC704 ?
YES TYPE 1 ,NO TYPE 10
?1

```

FIG. 3.8a. A METHOD OF ACTIVATING SUBROUTINE 1.

```

NUMBER OF Y DIVISONS (ANY NUMBER)?
?8
NUMBER OF ZETA DIVISONS (ANY NUMBER)?
?7
INCREMENT REQUIRED ON Y AXIS (CM)
?0.05
TIME INCREMENT REQUIRED (SEC)?
?1.0
PREHEAT TEMPERATURE (DEG C)?
?22
WELDING VOLTAGE (VOLTS)?
?70000
WELDING CURRENT (AMPS)?
?0.03
WELDING SPEED (IN/MIN)?
?10
PLATE THICKNESS (IN)?
?0.5

```

FIG. 3.8b. INPUT DATA TO SUBROUTINE 1.

WELDING PARAMETERS:

```

THERMAL CONDUCTIVITY TK= .100 CAL/CM-S-DC
THERMAL DIFFUSIVITY ALFA= .065 CM**2/S
PREHEAT TEMPERATURE TO= 22.0 DEG C
PLATE THICKNESS H= 1.27 CM
WELDING POWER(EFFECTIVE) Q= 1785.0 J/S
HEAT INPUT PER UNIT THICKNESS QPUT1= 3570.0 J/S-IN
HEAT INPUT PER UNIT THICKNESS QPUT2= 1405.5 J/S-CM
HEAT INPUT PER UNIT AREA QPUA1= 21420.0 J/IN*2
HEAT INPUT PER UNIT AREA QPUA2= 3320.1 J/CM*2
HEAT INPUT PER UNIT AREA QPUA3= 33.2 J/MM*2
HEAT INPUT PER UNIT AREA QPUA4= 21.4 KJ/IN*2
HEAT INPUT PER UNIT AREA QPUA5= 3.3 KJ/CM*2
HEAT INPUT PER UNIT AREA QPUA6= .03 KJ/MM*2
HEAT INPUT PER CALORIES QPC= 336.1 CAL/S-CM
WELDING VOLTAGE VT= 20000.0 VOLTS
WELDING CURRENT A= .030 AMPS
WELDING SPEED V= .423 CM/S
WELDING EFFECIENCY EFF= .85

```

FIG. 3.8c. THERMAL CONSTANTS AND WELDING PARAMETERS ECHOED BACK FROM SUBROUTINE 1.

is written out and the necessary units follow in brackets. The user must submit the data in the required units, Fig. 3.8b.

In order to inform the user of the assumed constants contained in the program, and to display the weld parameters (to ensure correct input data), a number of quantities are echoed back on the read-out display as shown in Fig. 3.8c.

3.4.2 The Temperature Distribution Matrix

Fig. 3.8d is a typical readout from subroutine 1, that corresponds to the input data indicated in Fig. 3.8b. The table of computations displays the three variables which are included in the calculation of the temperature distribution, namely, the time (sec), the distance zeta (cm) and the increment of distance Y (cm) in the two-dimensional case (or R(cm) in the three-dimensional case). Under the "Y(cm)" heading, the first row shows the selected values of Y. The remaining rows show the calculated values of the temperature. In the sample shown, the user has selected eight values for Y starting from 0.0 cm to 0.35 cm with an incremental increase of 0.05 cm.

The first column lists the time t (sec), which increases according to the increment of time given by the user (in this case, the increment equals one second). The second column lists the distance ξ (cm) along weld centreline. The columns, three to ten, list the temperature $T(\xi, y)$ at each time t ($\xi = -vt$).

COMPUTED TEMPERATURE DISTRIBUTION T(ZETA,Y)
DEGREES CELSIUS

TIME (SEC)	ZETA (CM)	Y (CM)							
		.000	.050	.100	.150	.200	.250	.300	.350
-4.00	1.69	22.	22.	22.	22.	22.	22.	22.	22.
-3.00	1.27	22.	22.	22.	22.	22.	22.	22.	22.
-2.00	.85	24.	24.	24.	23.	23.	23.	23.	23.
-1.00	.42	56.	55.	54.	52.	50.	47.	45.	42.
.00	.00	9999.	1065.	716.	527.	404.	318.	255.	207.
1.00	-.42	554.	547.	528.	499.	462.	421.	378.	336.
2.00	-.85	410.	408.	402.	391.	377.	360.	341.	320.

FIG. 3.8d. TEMPERATURE DISTRIBUTION MATRIX.

ENTER MAXIMUM NUMBER OF ITERATION
7200

RATE OF COOLING AT TEMP =704 DEG C

Y (CM)	TIME (SEC)	ZETA (CM)	ROC DEG C
.000	.56	-.24	-824.
.050	.53	-.22	-783.
.100	.38	-.16	-587.
.150	NOT AVAILABLE AT THAT RADIUS		
.200	NOT AVAILABLE AT THAT RADIUS		
.250	NOT AVAILABLE AT THAT RADIUS		
.300	NOT AVAILABLE AT THAT RADIUS		
.350	NOT AVAILABLE AT THAT RADIUS		

FIG. 3.8e. CALCULATED COOLING RATES.

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3.4.3 The 704°C Cooling Rate Distribution

Once the listing of the temperature distribution matrix has been completed, the program asks the user to enter the maximum number of iterations for the half interval method. When the user supplies this information, the computer starts to calculate the time and zeta values corresponding to the 704°C quasi-stationary temperature isotherms, and computes the cooling rates at these values. Fig. 3.8e is the output in a table consisting of four columns. The first column lists the distance Y(cm), the second column lists the time (sec), the third column lists the distance zeta (cm) and the fourth column contains the rate of cooling (°C/sec). If the maximum temperature in any column of the temperature distribution matrix is other than 704°C, the computer types "not available at that radius" in front of the value of Y distance.

When the first subroutine is executed, the computer goes back to the master program and asks the user whether or not the second subroutine (ROC2D) is to be executed and so on until all six subroutines are probed. Fig. 3.8f is an example where the other subroutines are not required.

```

*****
DO YOU WANT ROC2D ?
YES TYPE 2 , NO TYPE 20
?20
*****
DO YOU WANT RWCL2D ?
YES TYPE 3 , NO TYPE 30
?30
*****
DO YOU WANT TD3D & ROC704 ?
YES TYPE 4 , NO TYPE 40
?40
*****
DO YOU WANT ROC3D ?
YES TYPE 5 , NO TYPE 50
?50
*****
DO YOU WANT RWCL3D ?
YES TYPE 6 , NO TYPE 60
?60
.*STOP* 0

```

FIG. 3.8f. THE REMAINING SUBROUTINE PROBES OF THE
MASTER PROGRAM.

NOTE: COMPLETE LISTING OF THE COMPUTER PROGRAM FOR THE PREDICTION
OF WELD HARDNESS IS SHOWN IN APPENDIX 7.

CHAPTER 4

COMPUTER MODEL CALCULATIONS (COOLING RATES)4.1 INTRODUCTION

To determine the hardness distribution across a weld, it is first necessary to calculate the 704°C cooling rate distribution using the computer model described in Chapter 3. In this Chapter, the 704°C cooling rate distribution is investigated for typical welding situations.

It is first necessary to decide on typical input welding conditions - in particular, heat inputs for the calculations. Following this, the 704°C cooling rates are calculated from the Myers et al² formulation and checked against the cooling rates obtained by graphical methods from the Rosenthal distribution. Having confirmed the authenticity of the program, cooling rate distributions for typical welds are calculated and examined.

4.2 HEAT INPUTS FOR THE CALCULATIONS

Welding processes can be classified roughly by heat input (low, medium or high). Typical heat input ranges for various welding techniques are shown in Table 4.1. Based on these "typical ranges", the heat inputs contained in Table 4.2 (two-dimensional) and Table 4.3 (three-dimensional) were selected for calculation purposes.

TABLE 4.1. TYPICAL WELD HEAT INPUTS.

2D, 3D AND WELD TYPE	TWO-DIMENSIONAL CASE (THIN PLATE)		THREE-DIMENSIONAL CASE (THICK PLATE)		WELD TYPES
	HEAT INPUT PER UNIT AREA (QPUA)		HEAT INPUT PER UNIT LENGTH (QPUL)		
	KJ/cm ²	KJ/in ²	KJ/cm	KJ/in	
HIGH HEAT INPUT (HH)	10-80	80-500	10-80	30-200	- SUBMERGED ARC - ELECTRO-SLAG AND ELECTRO-GAS WELDING
	3-15	20-100	4-15	10-40	- MANUAL ARC - TUNGSTEN INERT GAS (TIG) - METAL INERT GAS (MIG) - CO ₂ WELDING
LOW HEAT INPUT (LH)	0.4-3	2.5-20	0.4-4	1-10	- ELECTRON BEAM - LASER - PLASMA WELDING

TABLE 4.2. HEAT INPUT VALUES USED FOR TWO-DIMENSIONAL CALCULATIONS.

HEAT INPUT CLASSIFICATIONS HEAT INPUT UNITS	HIGH HEAT (HH)	MEDIUM HEAT (MH)	LOW HEAT (LH)
HEAT INPUT PER UNIT AREA QPUA (KJ/in ²)	107.1	21.4	10.7
HEAT INPUT PER UNIT AREA QPUA (KJ/cm ²)	16.6	3.3	1.7

TABLE 4.3. HEAT INPUT VALUES USED FOR THREE-DIMENSIONAL CALCULATIONS.

HEAT INPUT CLASSIFICATIONS HEAT INPUT UNITS	HIGH HEAT (HH)	MEDIUM HEAT (MH)	LOW HEAT (LH)
HEAT INPUT PER UNIT LENGTH QPUL (KJ/in)	53.5	10.7	5.4
HEAT INPUT PER UNIT LENGTH QPUL (KJ/cm)	21.1	4.2	2.1

4.3 COOLING RATE (704°C) CALCULATIONS

To check the calculations from the program, two different methods were used to find some of the 704°C cooling rates. The first method is based on the derivation of Myers et al², Eqns. (2.57) and (2.88). This is the routine method used by the program to calculate the 704°C cooling rate. The second method is a graphical routine based on the calculated temperature distribution from the Rosenthal theory, Eqns. (2.52) and (2.85). The fact that these two approaches provide the same cooling rate values lends considerable credibility to the program.

The 704°C cooling rates based on Myers² approach is routinely supplied by the computer program described in Chapter 3 (e.g. Fig. 3.8e). The other method of calculating the 704°C makes use of the quasi-stationary temperature distribution calculated from the Rosenthal theory such as that shown in Fig. 3.8d. The temperature data are plotted against time, and the cooling rate extracted as the slope at 704°C. Such a plot is shown in Fig. 4.1. A comparison of the centreline cooling rates for both methods is shown in Table 4.4. It is apparent from the data contained in the table that there is very good agreement. While there is some difficulty in extracting the cooling rate graphically (it is sensitive to plotting accuracy), the agreement is sufficient to provide considerable confidence in the results.

FIG. 4.1... COOLING RATE AT 704°C (THREE-DIMENSIONAL CASE, HIGH HEAT INPUT AT WELD CENTRELINE), $V=70\text{KV}$, $I=0.03$ amperes, $v=2$ ipm, and $T_0=22^\circ\text{C}$.

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TABLE 4.4. COMPARISON OF COOLING RATE CALCULATIONS.

HEAT INPUT AND WELD CASE	COOLING RATES AT WELD CENTRELINE	
	FROM TIME- TEMPERATURE CURVES	FROM COMPUTER MODEL
HH*-2D**	-30	-33
MH-2D	-826	-824
LH-2D	-3280	-3294
HH-3D	-55	-58
MH-3D	-295	-290
LH-3D	-588	-580

* HH, MH AND LH REFER TO: HIGH, MEDIUM AND LOW HEAT INPUTS

** 2D, 3D REFER TO: TWO- AND THREE-DIMENSIONAL CASES

4.4 COOLING RATES DISTRIBUTION ACROSS A WELD

4.4.1 Two-Dimensional Case

Fig. 4.2a shows the distribution of the cooling rates across the weld in the case of high heat input. It can be seen that the maximum cooling rate (-33°C/sec) is at the weld centreline ($Y=0.0$). It remains almost constant near the weld centreline then gradually decreases to -23°C/sec at the HAZ boundary ($Y=0.5$).

In the case of medium heat input, the maximum cooling rate equals -824°C/sec at the weld centreline. It decreases remarkably as we depart from the weld centreline as shown in Fig. 4.2b. It can be noticed that the total heat-affected area is considerably smaller and the cooling rate values are higher than the high heat input weld.

In the case of the low heat input weld, the maximum cooling rate is at the weld centreline ($-3294^{\circ}\text{C/sec}$) and decreases sharply through the weld as shown in Fig. 4.2c. In general, cooling rates are very rapid and the total heat affected area (FZ + HAZ) is small.

From Figs. 4.2a, 4.2b and 4.2c, the following observations are apparent:

1. The maximum cooling rate is at the weld centreline for all cases (high, medium and low heat input).
2. The two-dimensional cooling rates are very sensitive to heat input. The most rapid cooling rate among the three cases is for the low heat input.

2 2
OF / DE

FIG. 4.2. CALCULATED* COOLING RATE DISTRIBUTIONS FOR TWO-DIMENSIONAL WELDS.

- a) High heat input, 16.6 kJ/cm²
- b) Medium heat input, 3.3 kJ/cm²
- c) Low heat input, 1.7 kJ/cm²

* See Appendix 3.

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3. In general, there is about a 25-30% difference in cooling rate between the centreline and HAZ boundary.

4.4.2 Three-Dimensional Case

The three-dimensional cooling rate distribution for the high heat input (21.1 KJ/cm) is shown in Fig. 4.3a. From the figure, it can be seen that the maximum cooling rate is -58°C/sec at the weld centreline and decreases gradually across the weld to -37°C/sec . It is also apparent that the total heat affected area (FZ + HAZ) is relatively large and the cooling rate values are relatively low.

Fig. 4.3b shows the cooling rate distribution across the medium heat input weld (4.2 KJ/cm). It can be seen from this figure that the maximum cooling rate is -290°C/sec at the weld centreline and decreases across the weld to -131°C/sec at the HAZ boundary.

In the case of low heat input (2.1 KJ/cm), Fig. 4.3c, the maximum cooling rate is -580°C/sec at the weld centreline. The shape of the curve changes smoothly to the lowest cooling rate of -553°C/sec at $Y=0.2\text{ cm}$.

From Figs. 4.3a, 4.3b and 4.3c, we notice that:

1. The maximum cooling rate is at the weld centreline for all cases (high, medium and low heat input).
2. The three-dimensional cooling rates are sensitive to heat input. The most rapid cooling rate among the three cases is for the low heat input.
3. There is about a 5-50% difference in cooling rate between the centreline and the HAZ boundary.

FIG. 4.3. CALCULATED COOLING RATE DISTRIBUTIONS FOR THREE-DIMENSIONAL WELDS.

- a) High heat input, 21.1 KJ/cm^2
- b) Medium heat input, 4.2 KJ/cm^2
- c) Low heat input, 2.1 KJ/cm^2

* See Appendix 3.

4.4.3 Comparison Between Two- and Three-Dimensional Cooling Rates

Referring to Figs. 4.2 and 4.3, the following can be concluded:

1. Two-dimensional cooling rates are higher than three-dimensional cooling rates for the heat levels used in this thesis. (Note that these are typical heat levels used in practice.)
2. Total heat affected width for the three-dimensional case is wider than it is for the two-dimensional case.
3. Two-dimensional cooling rates are more sensitive to heat input than three-dimensional cooling rates.
4. The cooling rate distribution is almost flat near the weld centreline for the three-dimensional case, while it varies considerably for the two-dimensional.

CHAPTER 5

PREDICTING WELD HARDNESS*5.1 SELECTION OF STEELS

In order to predict weld hardness by comparing the calculated weld cooling curves with Jominy data, different SAE* steels were selected. The carbon content, the hardenability, and the available Jominy data were the main considerations for selecting these steels. The steels that were selected are listed below:

1. The carbon content series selected is SAE1021, SAE1045 and SAE1095.
2. The hardenability series selected is SAE1035, SAE4130 and SAE4340.

5.2 HARDNESS PREDICTION FOR STEELS OF DIFFERENT CARBON CONTENTS
SAE(1021, 1045 and 1095)

These steels were selected mainly to cover a wide variety of steels from low carbon content ($\% C < 0.25$) to high carbon levels ($\% C > 0.6$). Jominy data for these steels were extracted from References 14 and 15.

Figs. 5.1, 5.2 and 5.3 show the $704^{\circ}C$ cooling rate versus hardness of the Jominy end quench data for the SAE (1021, 1045 and 1095) steels.

* SAE: Society of Automotive Engineers

FIG. 5.1. HARDENABILITY CURVE FOR 1021 STEEL.

$C=0.20$
 $M_n=0.81$
 n

FIG. 5.2. HARDENABILITY BAND FOR 1045 STEEL.

$C=0.45$
 $M_n=0.75$
 $S_i^n=0.23$

FIG. 5.3. HARDENABILITY CURVE FOR 1095 STEEL.

$C=0.89$
 $M_n=0.29$
 n

Fig. 5.2 shows an example of a hardenability band. This difference of measured hardness for the same cooling rate (hardenability band) is mainly due to differences of chemical compositions, experimental arrangements, conditions, and accuracy of measurements. In such cases, it was decided to use a mean curve through the hardenability band to match with other cases where there is only an average curve of hardenability available. By comparing the 704 °C cooling rate distribution presented in Chapter 4 with these figures, hardness distributions can be predicted.

Figs. 5.4a, 5.4b and 5.4c show the hardness distribution curves. From these hardness distribution curves, it can be seen that:

1. The hardness values increase as the carbon content increases.
2. The extent of the hardened zone (heat affected area) increases as the heat input increases.
3. The hardness of the weld decreases as the heat input increases.
4. The hardness distribution does not change significantly across the weld for most cases.
5. The maximum hardness is always located at weld centreline which is expected since the maximum cooling rate occurs in this position in Figs. 4.2 and 4.3.

5.3 HARDNESS PREDICTION FOR STEELS OF DIFFERENT HARDENABILITY SAE (1035, 4130 and 4340)

These types of steels were selected to cover the three levels of steel hardenability, namely: low hardenability steel (for example, plain carbon steels), medium hardenability steel (for example, chromium-

FIG. 5.4. HARDNESS DISTRIBUTION* FOR THE CARBON STEEL SERIES, AND THREE HEAT INPUT LEVELS (HIGH HEAT HH, MEDIUM HEAT MH AND LOW HEAT LH).

a) SAE1021

b) SAE1045

c) SAE1095

* See Appendix 4.

• Hardness values for LH and MH are the same.

molybdenum steels), and high hardenability steel (for example, chromium-molybdenum-nickel steel). Information about these steels has been obtained from References 14 and 15. The Jominy end quench data for these steels is shown in Figs. 5.5, 5.6 and 5.7.

The hardness distribution curves for these steels are shown in Figs. 5.8a, 5.8b and 5.8c. From these figures, it can be concluded that:

1. While the hardness is expected to increase as the hardenability increases, this would seem to be a weak effect for the series in this investigation. In fact, the hardness is at a high level (saturated due to a fully martensitic condition) for all heat inputs. Any variation in hardness is probably not due to hardenability but may be attributed to small differences in carbon level and other such effects. The results certainly indicate that high hardness welds are to be expected for any steel with a hardenability of greater than SAE1035 which is rather astounding since this is the majority of steels. General practice would confirm this fact and thereby the credibility of the model.
2. The hardness distributions across these welds are almost constant for all heat inputs. This lends support to the use of the centreline condition for calculating the weld hardness of steels with a hardenability in excess of the hardenability of SAE1035.

FIG. 5.5. HARDENABILITY CURVE FOR 1035 STEEL.

$$C=0.35$$

$$M_n=0.37$$

FIG. 5.6. HARDENABILITY BAND FOR 4130 STEEL.

$$C=0.30$$

$$M_n=0.50$$

$$S_n^i=0.25$$

$$C^i=0.98$$

$$M_o^r=0.20$$

FIG. 5.7. HARDENABILITY BAND FOR 4340 STEEL.

$$C=0.40$$

$$M_n=0.73$$

$$S_n^i=0.25$$

$$N^i=1.78$$

$$C^i=0.80$$

$$M_o^r=0.25$$

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FIG. 5.8. HARDNESS DISTRIBUTION* FOR THE HARDENABILITY STEEL SERIES AND THREE HEAT INPUT LEVELS (HIGH HEAT, HH, MEDIUM HEAT, MH, AND LOW HEAT, LH).

a) SAE1035

b) SAE4130

c) SAE4340

* See Appendix 4.

• Hardness values for LH, MH and HH are the same

▲ Hardness values for MH and HH are the same

5.4 DISCUSSION

Predicting hardness from Jominy data would seem to be hazardous. As pointed out in the previous two sections, there is considerable inaccuracy in the Jominy results. For a given cooling rate, the hardenability band would suggest a possible error of perhaps 10 R_C points for most steels. At the same time, there is bound to be considerable error in the calculated cooling rates because of all the assumptions necessary to arrive at the Rosenthal and Myers formulations (e.g. point and line heat sources, infinite plates, temperature insensitivity, thermal properties, etc.). In addition to these effects, there is the overall assumption that only the cooling rates at 704°C have to be matched and that prior and subsequent thermal histories are not strongly significant.

It is difficult to assess the importance of all these effects and hence judge the sensitivity of the model. On the other hand, the predicted results do appear to be of the right order of magnitude based on general experience. In many cases, such as the high hardenability welds, the hardness is saturated at the martensite level and this decreases the effect of the cooling rate approximations. In other cases (high heat input and low carbon content), low hardnesses are predicted (saturated to some extent at the pearlite level) and once again the importance of cooling rate and other assumptions are decreased.

In the transition region, the assumptions take on much more serious overtones. However, in practice, the transition region is sometimes less important than the saturated regions. The saturated

regions usually cover a wide range of operating conditions, while the transition region is comparatively smaller for many steels. At the very least, this method is useful for distinguishing between the fully hardened and fully softened weld conditions, and this is expected to be quite useful in practice. It is, however, also possible that rough predictions in the transition area are valid since the results indicate that transition softening is predicted for the plain carbon materials. A better assessment of this possibility has to await experimental experience. To initiate this, predicted hardness values are compared to some available experimental values in Chapter 7.

As indicated previously, some Jominy data is presented in terms of a hardenability band. This is particularly true of the so-called hardenability steels, i.e. those steels designed specifically for machine parts. Such a hardenability band is shown in Figs. 5.2, 5.6 and 5.7. In heat-treating practice, the lower limit of these bands is used to ensure fully hardened sections. In welding practice, it would seem that the upper part of the band should be used as this represents a "worst case condition", i.e. the highest hardness values are predicted. Mean values are used in this thesis because not all available Jominy data were banded and worst case calculations prevent comparisons between steels.

Since the heat input (Q) and the cooling rate (dT/dt) are related through Eqns. (2.57) and (2.88) for two- and three-dimensional heat flow, the cooling rate axis of the Jominy diagram can be replaced

by a heat input. A heat input of Joules/in² is used for the two-dimensional case and Joules/in for the three-dimensional case shown in Figs. 5.9. Such a transformation is expected to be of considerable convenience to practicing engineers because it eliminates, to some extent, the need for the computer program. Weld hardnesses can be extracted directly from this arrangement if the heat input is known. The heat input is, of course, a relatively straightforward calculation from the welding voltage, current, speed and plate thickness (for the two-dimensional case). In addition, an efficiency is needed which can be obtained from Christensen's work, Fig. 2.3. These data are then substituted into Eqns. (2.1), (2.4) and (2.5) to obtain the heat input. Such a diagram can perhaps be called a Jominy-welding diagram.

(a) TWO-DIMENSIONAL CASE

(b) THREE-DIMENSIONAL CASE

FIG. 5.9. JOMINY-WELDING DIAGRAM.

CHAPTER 6

EFFECT OF PREHEAT TEMPERATURE ON WELD HARDNESS6.1 THE HARDNESS PRACTICAL LIMIT

One of the most commonly applied rules in welding is that the hardness should not be allowed to exceed $35 R_C$ (350 VPN)⁶. Referring to Figs. 5.4 and 5.8, the hardness values exceed $35 R_C$ in most cases. In order to reduce the hardness to values below $35 R_C$, preheat is often used to reduce the rate of cooling. Reducing the rate of cooling reduces the weld hardness as shown in Figs. 5.1, 5.2 and 5.3.

6.2 CALCULATED EFFECT OF PREHEAT ON WELD HARDNESS

To study the effect of preheat on weld centreline hardness, the calculations contained in Chapter 5 were simply repeated here using the additional variable T_0 (preheat) in Eqns. (2.52) and (2.88). Preheat temperature from 20°C to 300°C were investigated as this was thought to be a practical range in welding practice. Just as in the investigation described in Chapter 5, the steels were of two series - one a plain carbon series (from low carbon to high carbon - SAE1021, SAE1045 and SAE1095) and the other a hardenability series (SAE1035, SAE4130 and SAE4340). The heat inputs are contained in Tables 4.2 and 4.3. The results of these calculations are shown in Figs. 6.1 and 6.2.

2D CASE

(a)

3D CASE

94.

(b)

(c)

FIG. 6.1. HARDNESS AND PREHEAT TEMPERATURE* RELATIONSHIP FOR THE CARBON STEEL SERIES AND THREE HEAT INPUT LEVELS (HIGH HEAT HH, MEDIUM HEAT MH AND LOW HEAT LH).

a) SAE1021

b) SAE1045

c) SAE1095

* See Appendices 5 and 6.

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FIG. 6.2. HARDNESS AND PREHEAT TEMPERATURE* RELATIONSHIP. FOR THE HARDENABILITY STEEL SERIES AND THREE HEAT INPUT LEVELS (HIGH HEAT HH, MEDIUM HEAT MH AND LOW HEAT LH).

- a) SAE1035
- b) SAE4130
- c) SAE4340

* See Appendices 5 and 6.

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6.3 OBSERVATIONS AND DISCUSSION

From Figs. 6.1 and 6.2, the following can be said:

- (1) Preheats (20-300°C) do not significantly reduce the hardness of any of the cases considered where there is two-dimensional heat flow. Apparently, higher preheat temperatures are necessary before a hardness decrease is possible.
- (2) In general, there seems to be some reduction in hardness where the heat flow is three-dimensional.
 - (i) Hardness values decrease significantly with preheat (20-300°C) for the low and medium carbon steels.
 - (ii) Only the low carbon (SAE1021) and medium carbon (SAE1045) steels responded to preheat enough to lower their hardness values below R_C 35. Even then, the hardness of SAE1045 is only lowered below this value where the heat input is high.
 - (iii) There is only a small decrease in hardness for the high carbon and high hardenability materials.
- (3) In general, the present study shows that preheats in the range from (20-300°C) do not seem to decrease the hardness as much as might reasonably be expected. An experimental investigation of these results should be conducted to assess the significance of the use of the Jominy concept for determining preheat temperatures. At the same time, the schematic diagram shown in Fig. 6.3 is suggested for any future investigation in this area where preheats are high enough to cause significant softening. Such a diagram would present the practicing engineer with an immediate (albeit rough) estimate of the preheat needed for a weld.

FIG. 6.3. RELATIONSHIP BETWEEN WELD HARDNESS AND PREHEAT TEMPERATURE.

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CHAPTER 7

COMPARISON OF PREDICTED AND MEASURED WELD HARDNESS7.1 COMPARISON BETWEEN PREDICTED HARDNESS AND EXPERIMENTALLY MEASURED HARDNESS FROM THE WORK OF BIBBY ET AL³

Bibby and Goldak³ have carried out experimental measurements of weld hardness for the steels SAE(1020, 1045, 1095, 1035, 4130 and 4340). These were electron beam welded (two-dimensional heat flow) with the following welding parameters:

70KV, 25mA, $v=15$ in/min, $h=3/16$ in and $T_0 = 25^\circ\text{C}$

These same parameters were used to predict weld hardness by the computer model. A comparison of hardness has been made at weld centreline.

Table 7.1 presents a comparison between hardness predicted by the computer model and the measured hardness. The predicted hardness shows good agreement with those measured by the investigators.

7.2 COMPARISON BETWEEN PREDICTED HARDNESS AND EXPERIMENTALLY MEASURED HARDNESS FROM THE WORK OF GVILDYS⁴

This comparison is shown in Table 7.2. Once again, there would seem to be good agreement between the predicted results and the measured values.

7.3 DISCUSSION

The overall agreement of the predicted values with the experimental results lends some credibility to the model. It is, however, fully acknowledged that much more experimental experience is needed before the sensitivity of the method can be assessed.

TABLE 7.1. COMPARISON BETWEEN PREDICTED AND EXPERIMENTALLY MEASURED WELD HARDNESS FOR SIX STEELS.

SAE STEEL	HARDNESS (VPN)	
	PREDICTED*	MEASURED**
1021	372	330
1045	733	690
1095	816	825
1035	577	550
4130	528	415
4340	613	620

* HARDNESS PREDICTED AT THE WELD CENTRELINE

** 1 - VALUES EXTRACTED FROM THE EXPERIMENTAL INVESTIGATION OF BIBBY ET AL³

2 - THROUGH THICKNESS ELECTRON BEAM WELDS

V=70 KV, I=0.025 amperes, v=15 in/min, h=3/16 in and T₀=25°C

TABLE 7.2. COMPARISON BETWEEN PREDICTED AND EXPERIMENTALLY MEASURED WELD HARDNESS FOR SAE1045.

HEAT INPUT (Q) KJ/in	WELD CASE (2D or 3D)	HARDNESS (VPN)	
		PREDICTED	MEASURED*
7.14	3D	674	750
11.9	3D	528	520
71.4	3D	336	320
142.8**	2D	310	320

VALUES EXTRACTED FROM THE EXPERIMENTAL INVESTIGATION OF GVILDYS⁴

** HEAT INPUT UNITS IS KJ/in²

While the agreement looks reasonable, the author is reluctant to even estimate the sensitivity of the method because of the highly scattered Jominy data that is available among other things. However, for the reasons discussed in Chapter 5, it is felt that the method is reasonably good where the hardness is saturated at the fully hardened level (martensite) or at the fully softened level (pearlite).

In the transitional region, the results do indicate reasonable agreement. Whether this is fortuitous or, in fact, real will have to await further investigation.

CHAPTER 8

CONCLUSIONS8.1 CONTRIBUTIONS

- (1) A computer program has been developed to calculate the cooling rate distribution at 704°C of a weld. The program covers a variety of heat inputs as well as both two- and three-dimensional heat flow.
- (2) A theoretical method of predicting weld hardness has been developed based on a comparison of calculated weld cooling rates with Jominy end quench data.
- (3) Preliminary verification of predicted hardness values has been carried out through comparisons with available experimental data.
- (4) The use of the model for predicting preheat temperature has been demonstrated. A useful preheat-hardness diagram has been proposed for the practicing engineer.
- (5) To simplify the use of this method in practice, it is suggested that the cooling rate axis of the Jominy diagram should be changed to heat input (i.e. a Jominy-welding diagram).

8.2 CONCLUSIONS

- (1) From the Rosenthal-Myers theory, it has been shown that, in general, the cooling rate at 704°C varies about 20-50% across a weld and that weld cooling rates are very sensitive to the heat input.

- (2) An approximate weld hardness can be predicted theoretically by comparing the computed 704°C cooling rate with the 704°C cooling rate versus hardness relationship provided by the Jominy end quench data.
- (3) Predicted weld hardness increases as carbon content increases and to a much lesser extent as the hardenability of steel increases. It decreases significantly as heat input increases.
- (4) The model predicts that preheat temperatures in the range ($20-300^{\circ}\text{C}$) decreases the weld hardness of the low carbon - low hardenability steels. However, for the high carbon content and high hardenability steels, the effect of preheat temperature is not significant.
- (5) A comparison of predicted hardnesses and available experimental values suggests that the model proposed in this thesis can be used to predict weld hardness.

8.3 FURTHER WORK

- (1) Predicted hardness using the Jominy approach should be compared to weld hardness determinations of other recent approaches, such as the Japanese method of Arata¹⁷ and the French method of Bastien¹⁸.
- (2) To obtain a better experimental base, the results should be extended to include other kinds of alloy steels.
- (3) The thesis has examined the effect of preheat temperature within the range of $20-300^{\circ}\text{C}$. Weld hardness of most kinds of steels considered in this study have not been affected significantly

to the extent of going below the hardness limit of 35 R_C. An extension of the preheat temperature range over 300°C would provide a better background in this area.

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APPENDIX 1

BESSEL FUNCTIONS*¹⁶

Polynomial Approximations

In equations 1.1 to 1.4, $t = x/3.75$.

$$1.1 \quad -3.75 \leq x \leq 3.75$$

$$I_0(x) = 1 + 3.51562 \, 29t^2 + 3.08994 \, 24t^4 + 1.20674 \, 92t^6 \\ + .26597 \, 32t^8 + .03607 \, 68t^{10} + .00458 \, 13t^{12} + \epsilon$$

$$|\epsilon| < 1.6 \times 10^{-7}$$

$$1.2 \quad 3.75 \leq x < \infty$$

$$x^2 e^{-x} I_0(x) = .39894 \, 228 + .01328 \, 592t^{-1} \\ + .00225 \, 319t^{-2} - .00157 \, 565t^{-3} \\ + .00916 \, 281t^{-4} - .02057 \, 706t^{-5} \\ + .02635 \, 537t^{-6} - .01647 \, 633t^{-7} \\ + .00392 \, 377t^{-8} + \epsilon$$

$$|\epsilon| < 1.9 \times 10^{-7}$$

$$1.3 \quad -3.75 \leq x \leq 3.75$$

$$x^{-1} I_1(x) = \frac{1}{2} + .87890 \, 594t^2 + .51498 \, 869t^4 \\ + .15084 \, 934t^6 + .02658 \, 733t^8 \\ + .00301 \, 532t^{10} + .00032 \, 411t^{12} + \epsilon$$

$$|\epsilon| < 8 \times 10^{-8}$$

$$1.4 \quad 3.75 \leq x < \infty$$

$$x^2 e^{-x} I_1(x) = .39894 \, 228 - .03988 \, 024t^{-1} \\ - .00362 \, 018t^{-2} + .00163 \, 801t^{-3} \\ - .01031 \, 555t^{-4} + .02282 \, 967t^{-5} \\ - .02895 \, 312t^{-6} + .01787 \, 654t^{-7} \\ - .00420 \, 059t^{-8} + \epsilon$$

$$|\epsilon| < 2.2 \times 10^{-7}$$

* POLYNOMIAL APPROXIMATIONS FOR THE BESSEL FUNCTIONS USED
IN EQNS. (2.52) AND (2.57)

CONTINUE (APPENDIX 1)

1.5

$$0 < x \leq 2$$

$$\begin{aligned} K_0(x) = & -\ln(x/2)I_0(x) - .57721\ 566 \\ & + .42278\ 420(x/2)^2 + .23069\ 756(x/2)^4 \\ & + .03488\ 590(x/2)^6 + .00262\ 698(x/2)^8 \\ & + .00010\ 750(x/2)^{10} + .00000\ 740(x/2)^{12} + \epsilon \end{aligned}$$

$$|\epsilon| < 1 \times 10^{-8}$$

1.6

$$2 \leq x < \infty$$

$$\begin{aligned} x^3 e^x K_0(x) = & 1.25331\ 414 - .07832\ 358(2/x) \\ & + .02189\ 568(2/x)^2 - .01062\ 446(2/x)^3 \\ & + .00587\ 872(2/x)^4 - .00251\ 540(2/x)^5 \\ & + .00053\ 208(2/x)^6 + \epsilon \end{aligned}$$

$$|\epsilon| < 1.9 \times 10^{-7}$$

1.7

$$0 < x \leq 2$$

$$\begin{aligned} xK_1(x) = & x \ln(x/2)I_1(x) + 1 + .15443\ 144(x/2)^2 \\ & - .67278\ 579(x/2)^4 - .18156\ 897(x/2)^6 \\ & - .01919\ 402(x/2)^8 - .00110\ 404(x/2)^{10} \\ & - .00004\ 686(x/2)^{12} + \epsilon \end{aligned}$$

$$|\epsilon| < 8 \times 10^{-9}$$

1.8

$$2 \leq x < \infty$$

$$\begin{aligned} x^3 e^x K_1(x) = & 1.25331\ 414 + .23498\ 619(2/x) \\ & - .03655\ 620(2/x)^2 + .01504\ 268(2/x)^3 \\ & - .00780\ 353(2/x)^4 + .00325\ 614(2/x)^5 \\ & - .00068\ 245(2/x)^6 + \epsilon \end{aligned}$$

$$|\epsilon| < 2.2 \times 10^{-7}$$

For expansions of $I_0(x)$, $K_0(x)$, $I_1(x)$, and $K_1(x)$ in series of Chebyshev polynomials for the ranges $0 \leq x \leq 8$ and $0 \leq 8/x \leq 1$, see [9.37].

APPENDIX 2
HALF INTERVAL METHOD¹³

To determine the coordinates of a point x located on temperature-time curve (Fig. A2.1) by the computer, the half-interval, or binary search method is used. This consists of evaluating the function at the midpoint of an arbitrary interval and then retaining the half-interval containing the coordinates of 704°C . The method is repeated until the 704°C coordinates are obtained with the desired accuracy.

The method is shown in detail in Fig. A2.1 and the processes are indicated by the flow chart in Fig. A2.2 as follows:

1. The required point x (704°C , time) is located between the two temperatures TEMP1 and TEMP2 , hence the temperature medium is:

$$\text{TEMP}_{\text{mid}} = \frac{\text{TEMP1} + \text{TEMP2}}{2}$$

$$\text{TEMP}_{\text{test}} = \text{TEMP}_{\text{mid}} - 704^{\circ}\text{C}$$

This step is indicated by box 2 - Fig. A2.2.

2. The mid-temperature is checked to find out if it is equal, below or above the required value as follows:
 - a) If $\text{TEMP}_{\text{test}} \cdot \text{TEMP1} = 0$,
 - * GO TO 3.6 and CALCULATE ROC.
 - b) If $\text{TEMP}_{\text{test}} \cdot \text{TEMP1} < 0$,
 - take $\text{TEMP1} = \text{TEMP}_{\text{mid}}$ rectangle 34
 - check the value $\text{TEMP2} - \text{TEMP1} \leq \text{ERROR}$ or the number of iterations, calculate at rectangle 3.6 and give final results

FIG. A2.1. HALF-INTERVAL METHOD TO FIND THE POINT x.

FIG. A2.2. HALF INTERVAL METHOD FLOW CHART.

- if $TEMP2 - TEMP1 > ERROR$ or the number of iterations is less than a present number, GO TO rectangle 3.2 and make another iteration
- c) If $TEMP_{test} - TEMP1 > 0$
 - take $TEMP2 = TEMP_{mid}$ rectangle 3.5
 - check that the value $TEMP2 - TEMP1 \leq ERROR$ or that the number of iterations is exceeded and calculate at rectangle 3.6 to give final results
 - if $TEMP2 - TEMP1 > ERROR$ or the number of iterations is not exceeded go to the rectangle 3.2 and make another iteration

APPENDIX 3. COOLING RATE DISTRIBUTION*.

Y** OR R**	COOLING RATE DISTRIBUTION					
	HIGH HEAT (IH)		MEDIUM HEAT (MH)		LOW HEAT (LI)	
	2D	3D	2D	3D	2D	3D
0.0	-33	-58	-824	-290	-3294	-580
0.03	-	-	-	-	-3052	-
0.05	-	-	-783	-	-2349	-
0.1	-33	-58	-587	-288	-	-576
0.2	-32	-57	-	-282	-	-553
0.3	-31	-55	-	-261	-	-
0.4	-28	-52	-	-131	-	-
0.5	-23	-47	-	-	-	-
0.6	-	-37	-	-	-	-

TABLE A3. COOLING RATE DATA USED TO GENERATE FIGURES 4.2 AND 4.3.

Y OR R IS A DISTANCE FROM WELD CENTRELINE (CM).

**

APPENDIX 4. HARDNESS DISTRIBUTION*

* TABLE A4. HARDNESS DISTRIBUTION DATA USED TO GENERATE
FIGURES 5.4 AND 5.8.

APPENDIX 4. HARDNESS DISTRIBUTION.

Y** OR R** (cm)	10.21						10.15						10.95					
	2D		3D		LH		2D		3D		LH		2D		3D		LH	
	HI R _C	MI R _C	HI R _C	MI R _C	HI R _C	MI R _C	HI R _C	MI R _C	HI R _C	MI R _C	HI R _C	MI R _C	HI R _C	MI R _C	HI R _C	MI R _C	HI R _C	MI R _C
0.0	2	38	38	6	29	38	31	58	58	42	58	58	40	65	43	63	65	65
0.03	-	-	28	-	-	-	-	-	58	-	-	-	-	-	65	-	-	-
0.05	-	38	28	-	-	-	-	58	58	-	-	-	-	65	-	-	-	-
0.1	2	38	-	6	29	38	31	58	-	42	58	58	40	65	43	63	65	65
0.2	2	-	-	6	28	38	31	-	-	41	58	58	40	-	43	63	65	65
0.3	2	-	-	6	24	-	30	-	-	40	58	-	40	-	43	62	-	-
0.4	2	-	-	5	15	-	29	-	-	39	58	-	40	-	42	58	-	-
0.5	1	-	-	4	-	-	28	-	-	37	-	-	40	-	41	-	-	-
0.6	-	-	-	3	-	-	-	-	-	32	-	-	-	-	40	-	-	-

** Y OR R IS A DISTANCE FROM WELD CENTRELINE

CONTINUE (APPENDIX 4)

Y** OR R** (cm)	1035						4130						4340					
	2D			3D			2D			3D			2D			3D		
	IH R _C	MH R _C	LH R _C	IH R _C	MH R _C	LH R _C	IH R _C	MH R _C	LH R _C	IH R _C	MH R _C	LH R _C	IH R _C	MH R _C	LH R _C	IH R _C	MH R _C	LH R _C
0.0	51	54	54	54	54	54	42	52	52	48	52	52	56	56	56	56	56	56
0.03	-	-	54	-	-	-	-	-	52	-	-	-	-	-	56	-	-	-
0.05	-	54	54	-	-	-	-	52	52	-	-	-	56	56	56	-	-	-
0.1	51	54	-	54	54	54	42	52	-	48	52	52	56	56	-	56	56	56
0.2	51	-	-	54	54	54	42	-	-	48	52	52	56	-	-	56	56	56
0.3	51	-	-	54	54	54	42	-	-	48	52	-	56	-	-	56	56	-
0.4	50	-	-	53	54	-	42	-	-	48	51	-	56	-	-	56	56	-
0.5	48	-	-	53	-	-	40	-	-	47	-	-	56	-	-	56	-	-
0.6	-	-	-	53	-	-	-	-	-	43	-	-	-	-	-	56	-	-

** Y OR R IS A DISTANCE FROM WELD CENTRELINE

APPENDIX 5

COOLING RATES AT WELD CENTRELINE*

PREHEAT TEMP (°C)	2D			3D		
	HH	MH	LH	HH	MH	LH
22	-33	-824	-3294	-58	-290	-580
50	-32	-790	-3158	-53	-267	-533
100	-30	-748	-2994	-45	-227	-455
150	-29	-716	-2865	-38	-191	-383
200	-24	-602	-2410	-32	-158	-317
250	-	+178	+712	-26	-128	-257
300	-	-106	-425	-20	-102	-203

* TABLE A.5 COOLING RATES DATA USED TO PREDICT HARDNESS VALUES
INDICATED IN APPENDIX 6.

APPENDIX 6. HARDNESS VALUES AT WELD CENTRELINE*

Preheat Temp. °C	1021			1045			1095		
	2D	3D	3D	2D	3D	3D	2D	3D	3D
	THI	LHI	MHI	THI	LHI	MHI	THI	LHI	MHI
22	2	38	6	58	58	42	40	65	65
50	2	38	5	58	58	39	40	65	65
100	2	38	4	58	58	35	40	65	65
150	2	38	3	58	58	32	40	65	65
200	2	38	2	58	58	30	40	65	64
250	-	-	1	-	-	29	-	-	63
300	-	-	1	-	-	28	-	-	61

TABLE A6. HARDNESS VALUES DATA USED TO GENERATE FIGURES 6.1 AND 6.2.

CONTINUE (TABLE A6)

Preheat Temp. °C	1035			4130			4340		
	2D	3D	3D	2D	3D	3D	2D	3D	3D
	III	LJI	III	III	LJI	III	III	LJI	III
22	51	54	54	42	52	48	52	56	56
50	51	54	54	42	52	48	52	56	56
100	50	54	53	42	52	46	52	56	56
150	50	54	53	42	52	43	52	56	56
200	48	54	51	42	52	42	52	56	56
250	-	-	49	-	-	40	51	-	56
300	-	-	47	-	-	37	50	-	56

APPENDIX 7. COMPUTER PROGRAM FOR THE PREDICTION OF
WELD HARDNESS.


```

1.000 C
2.000 C
3.000 C
4.000 C
5.000 C
6.000 C
7.000 C
8.000 C
9.000 C
10.000 C
11.000 C
12.000 C
13.000 C
14.000 C
15.000 C
16.000 C
17.000 C
18.000 C
19.000 C
20.000 C

```

```

000000
25.000 OUTPUT 'DO YOU WANT TD2D & ROC704 ?'
26.000 OUTPUT 'YES TYPE 1 ,NO TYPE 10 '
27.000 READ (2,1) SE
28.000 IF ( SE .EQ. 1 ) GO TO 100
29.000 IF ( SE .EQ. 10) GO TO 200
30.000 100 CALL TD2D
31.000 200 WRITE (3,2)
32.000 OUTPUT 'DO YOU WANT ROC2D ?'
33.000 OUTPUT 'YES TYPE 2 ,NO TYPE 20 '
34.000 READ (2,1) SE
35.000 IF ( SE .EQ. 2 ) GO TO 300
36.000 IF (SE .EQ. 20 ) GO TO 400
37.000 300 CALL ROC2D
38.000 400 WRITE (3,2)
39.000 OUTPUT 'DO YOU WANT RWCL2D ?'
40.000 OUTPUT 'YES TYPE 3 , NO TYPE 30 '

```

```

41.000      READ (2,1) SE
42.000      IF ( SE .EQ. 3 ) GO TO 500
43.000      IF ( SE .EQ. 30 ) GO TO 600
44.000      500 CALL RWCL2D
45.000      600 WRITE (3,2)
46.000      OUTPUT 'DO YOU WANT TD3D & ROC704 ?'
47.000      OUTPUT 'YES TYPE 4 , NO TYPE 40'
48.000      READ (2,1) SE
49.000      IF ( SE .EQ. 4 ) GO TO 700
50.000      IF ( SE .EQ. 40 ) GO TO 800
51.000      700 CALL TD3D
52.000      800 WRITE (3,2)
53.000      OUTPUT 'DO YOU WANT ROC3D ?'
54.000      OUTPUT 'YES TYPE 5 , NO TYPE 50'
55.000      READ (2,1) SE
56.000      IF ( SE .EQ. 5 ) GO TO 900
57.000      IF ( SE .EQ. 50 ) GO TO 1000
58.000      900 CALL ROC3D
59.000      1000 WRITE (3,2)
60.000      OUTPUT 'DO YOU WANT RWCL3D ?'
61.000      OUTPUT 'YES TYPE 6 , NO TYPE 60'
62.000      READ (2,1) SE
63.000      IF ( SE .EQ. 6 ) GO TO 1100
64.000      IF ( SE .EQ. 60 ) GO TO 1200
65.000      1100 CALL RWCL3D
66.000      1 FORMAT (1G)
67.000      2 FORMAT (X,70(' '))
68.000      1200 STOP
69.000      END
70.000 C
71.000 C
72.000 C
73.000 C
74.000 C
75.000 C
76.000 C
77.000 C
78.000 C
79.000 C
80.000 C
81.000 C

      SUBROUTINE TD2D
2D TEMPERATURE DISTRIBUTION AND ROC AT 704 BY MOHAMED EL-SHAYER , 1980
DIMENSION TIME(100) , ZETA(100) , Y(20) , TEMP(20,100)
EFF=0.85
PI=3.14159
TK=0.1
ALFA=0.065
S=4
      OUTPUT

```

```

82.000 OUTPUT 'NUMBER OF Y DIVISIONS (ANY NUMBER)?'
83.000 READ (2,1)NY
84.000 OUTPUT 'NUMBER OF ZETA DIVISIONS (ANY NUMBER)?'
85.000 READ (2,1)NZ
86.000 OUTPUT 'INCREMENT REQUIRED ON Y AXIS (CM)?'
87.000 READ (2,1)YIR
88.000 OUTPUT 'TIME INCREMENT REQUIRED (SEC)?'
89.000 READ (2,1)TIR
90.000 OUTPUT 'PREHEAT TEMPERATURE (DEG C)?'
91.000 READ (2,1)TO
92.000 OUTPUT 'WELDING VOLTAGE (VOLTS)?'
93.000 READ (2,1)VT
94.000 OUTPUT 'WELDING CURRENT (AMPS)?'
95.000 READ (2,1)A
96.000 OUTPUT 'WELDING SPEED (IN/MIN)?'
97.000 READ (2,1)V
98.000 OUTPUT 'PLATE THICKNESS (IN)?'
99.000 READ (2,1)H
100.000 OUTPUT
101.000 OUTPUT 'WELDING PARAMETERS:'
102.000 Q=VT*A*EFF
103.000 QPUT1=Q/H
104.000 QPUT2=Q/(H*2.54)
105.000 QPUA1=QPUT1/(V/60)
106.000 QPUA2=QPUT2/((V*2.54)/60)
107.000 QPUA3=QPUA2/100.0
108.000 QPUA4=QPUA1/1000.0
109.000 QPUA5=QPUA2/1000.0
110.000 QPUA6=QPUA3/1000.0
111.000 H=H*2.54
112.000 V=(V*2.54)/60.0
113.000 QPC=QPUT2/4.1819
114.000 WRITE(3,2) TN
115.000 WRITE(3,3) ALFA
116.000 WRITE(3,4) TO
117.000 WRITE(3,5) H
118.000 WRITE(3,6) Q
119.000 WRITE (3,7) QPUT1
120.000 WRITE (3,8) QPUT2
121.000 WRITE (3,9) QPUA1

```

```

122.000      WRITE (3,10) QFUA2
123.000      WRITE (3,11) QFUA3
124.000      WRITE (3,12) QFUA4
125.000      WRITE (3,13) QFUA5
126.000      WRITE (3,14) QFUA6
127.000      WRITE (3,15) QPC
128.000      WRITE (3,16) VT
129.000      WRITE (3,17) A
130.000      WRITE (3,18) V
131.000      WRITE (3,19) BFF
132.000      WRITE (3,20)
133.000      WRITE (3,21)
134.000      WRITE (3,22)
135.000      DO 90 I=1,8
136.000      DO 90 J=1,NN
137.000      90 TEMP(I,J) = 0.0
138.000      DO 100 I=1,NY
139.000      100 Y(I)=YIR*(I-1)
140.000      WRITE(3,23) (Y(I),I=1,NY).
141.000      DO 180 J=1,NZ
142.000      TIME(J)=-TIR*S
143.000      ZETA(J)=-V*TIME(J)
144.000      A = -V*ZETA(J)/(2.0*ALFA)
145.000      IF(A.GT.172) GO TO 160
146.000      DO 150 I=1,NY
147.000      R=SQRT(ZETA(J)**2.0+Y(I)**2.0)
148.000      IF (R.EQ. 0.0) GO TO 140
149.000      X=(V*R)/(2.0*ALFA)
150.000      IF(X. LE .2.0) GO TO 110
151.000      IF(X. GT .2.0) GO TO 120
152.000      110 T=X/3.75
153.000      CALL ND1(X,T,FKD)
154.000      GO TO 130
155.000      120 U=2.0/X
156.000      CALL ND2 (X,U,FKD)
157.000      130 TEMP(I,J)=T0+QPC*FKD*EXP(A)/(2.0*PI*TK)
158.000      GO TO 150
159.000      140 TEMP(I,J) = 9999.0
160.000      150 CONTINUE
161.000      WRITE(3,24) TIME(J), ZETA(J), (TEMP(I,J),I=1,NY)

```

```

162.000      GO TO 170
163.000      160 WRITE(3,30) TIME(J),ZETA(J)
164.000      OUTPUT'
165.000      170 S=S-1
166.000      180 CONTINUE
167.000      WRITE (3,25)
168.000      OUTPUT'
169.000      OUTPUT 'ENTER MAXIMUM NUMBER OF ITERATION'
170.000      READ(2,1) ITER
171.000      WRITE (3,26)
172.000      WRITE (3,27)
173.000      DO 220 I=1,NY
174.000      DO 190 J=1,NZ
175.000      JJ=NZ-J+1
176.000      IF ( TEMP(I,JJ) .GE. 704.0 ) GO TO 200
177.000      190 CONTINUE
178.000      GO TO 210
179.000      200 IF(TEMP(I,J).EQ.704.0) GO TO 230
180.000      IF ( JJ .EQ. NZ ) GO TO 210
181.000      TEMP1 = TEMP(I,JJ)
182.000      230 CALL N03 (I,JJ,ZETA,TIME,TN,QPC,V,ALFA,TO,R,Y,ROC,
183.000      C YROC,TIMROC,ZETROC,ITER,TEMP1)
184.000      WRITE (3,28) YROC,TIMROC,ZETROC,ROC
185.000      GO TO 220
186.000      210 WRITE (3,29) Y(I)
187.000      OUTPUT' NOT AVAILABLE AT THAT RADIUS'
188.000      220 CONTINUE
189.000      1 FORMAT (1G)
190.000      2 FORMAT (/, 'THERMAL CONDUCTIVITY TN=',F5.3,' CAL/CM-S-OC')
191.000      3 FORMAT (, 'THERMAL DIFFUSIVITY ALFA=',F5.3,' CM**2/S')
192.000      4 FORMAT (, 'PREHEAT TEMPERATURE TO=',F6.1,' DEG C')
193.000      5 FORMAT (, 'PLATE THICKNESS H=',F5.2,' CM')
194.000      6 FORMAT (, 'WELDING POWER(EFFECTIVE) Q=',F10.1,' J/S')
195.000      7 FORMAT (, 'HEAT INPUT PER UNIT THICKNESS QPUT1=',F10.1,' J/S-IN')
196.000      8 FORMAT (, 'HEAT INPUT PER UNIT THICKNESS QPUT2=',F10.1,' J/S-CM')
197.000      9 FORMAT (, 'HEAT INPUT PER UNIT AREA QPUA1=',F15.1,' J/IN**2')
198.000      10 FORMAT (, 'HEAT INPUT PER UNIT AREA QPUA2=',F15.1,' J/CM**2')
199.000      11 FORMAT (, 'HEAT INPUT PER UNIT AREA QPUA3=',F15.1,' J/MM**2')
200.000      12 FORMAT (, 'HEAT INPUT PER UNIT AREA QPUA4=',F10.1,' KJ/IN**2')
201.000      13 FORMAT (, 'HEAT INPUT PER UNIT AREA QPUA5=',F10.1,' KJ/CM**2')

```

```

202.000
203.000
204.000
205.000
206.000
207.000
208.000
209.000
210.000
211.000
212.000
213.000
214.000
215.000
216.000
217.000
218.000
219.000
220.000
221.000 C
222.000 C
223.000 C
224.000
225.000
226.000
227.000
228.000
229.000
230.000
231.000
232.000 C
233.000 C
234.000 C
235.000
236.000
237.000
238.000
239.000
240.000
241.000

14 FORMAT ('HEAT INPUT PER UNIT AREA QFUA6=',F10.2,' N./MM*2')
15 FORMAT ('HEAT INPUT PER CALORIES QPC=',F10.1,' CAL/S-CM')
16 FORMAT ('WELDING VOLTAGE VT=',F8.1,' VOLTS')
17 FORMAT ('WELDING CURRENT A=',F8.3,' AMPS')
18 FORMAT ('WELDING SPEED V=',F6.3,' CM/S')
19 FORMAT ('WELDING EFFICIENCY EFF=',F4.2,/)
20 FORMAT (15X,'COMPUTED TEMPERATURE DISTRIBUTION T(ZETA,Y)')
21 FORMAT (25X,'DEGREES CELSIUS')
22 FORMAT (/,'TIME (SEC)',4X,'ZETA (CM)',20X,'Y (CM)')
23 FORMAT (/,'24X,8F6.3,/)
24 FORMAT (1X,F8.2,3X,F8.2,4X,8F6.0,/)
25 FORMAT (X,70(' '))
26 FORMAT (10X,' RATE OF COOLING AT TEMP =704 DEG C')
27 FORMAT (/,'Y (CM)',5X,'TIME (SEC)',3X,'ZETA (CM)',8X,'ROC DEG C')
28 FORMAT (F6.3,4X,F7.2,6X,F7.2,8X,F12.0)
29 FORMAT (F9.3)
30 FORMAT (1X,F8.2,3X,F8.2)
RETURN
END

* * * * *
SUBROUTINE N01 (X,T,FND)
X=X/2.0
FND=1.0+3.515623*FND**2+3.0899424*FND**4+1.2067492*FND**6
C +0.2659732*FND**8+0.0360768*FND**10+0.0045813*FND**12
FK0=-ALOG(X)*FND-0.57721566+0.4227842*FND**2+0.23069756*FND**4+
C 0.0348859*FND**6+0.00262698*FND**8+0.0001075*FND**10+0.0000074*FND**12
RETURN
END

* * * * *
SUBROUTINE N02 (X,U,FND)
FK0=(EXP(-X)/SQRT(X))* (1.25331414 - 0.07832358 * U
C +0.0189568 * U**2 - 0.01062446 * U**3
C +0.00587872 * U**4 - 0.0025154 * U**5
C +0.00053208 * U**6 )
RETURN
END

```

```

242.000 C
243.000 C
244.000 C
245.000
246.000
247.000
248.000
249.000
250.000
251.000
252.000
253.000
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279.000
280.000
281.000

      * * * * *
      SUBROUTINE  NO3  (I,JJ,ZETA,TIME,TN,QPC,V,ALFA,TO,R,Y,
C          ROC,YROC,TIMROC,ZETROC,ITER,TEMP1)
      DIMENSION TIME(100) , ZETA(100) , Y(20)
      T1=TIME (JJ)
      T2=TIME (JJ+1)
      PI=3.14159
      YROC=Y(I)
      COUNT = 0.0
      TEMP1 = TEMP1 - 704
      TIMROC = (T1+T2) / 2.0
      ZETROC = -V*TIMROC
      CALL NO4(ZETROC,FKD,FK1,YROC,V,ALFA,R)
      A=(-V*ZETROC/(2.0*ALFA))
      IF (A .GT. 172) GO TO 218
      TEMROC=TO+QPC*EXP(A)*FKO/(2.0*PI*TK)-704
      GO TO 215
218 WRITE (3,1) Y(I)
      OUTPUT 'TEMROC IS NOT AVAILABLE AT THIS EXPONENTIAL'
      1 FORMAT (F5.3)
      GO TO 270
215 TEMMID = TEMROC
      TT = TEMP1 * TEMMID
      IF (TT) 220 , 260 , 240
220 T2 = TIMROC
      GO TO 250
240 TEMP1 = TEMMID
      T1 = TIMROC
250 TCHECK = T2-T1
      COUNT = COUNT + 1
      IF (ABS (TCHECK) .LE. 0.0001 .OR. COUNT .GT. ITER) GO TO 260
      GO TO 210
260 CALL NO4(ZETROC,FKD,FK1,YROC,V,ALFA,R)
      IF (R .EQ. 0.0) GO TO 270
      A=(-V*ZETROC/(2.0*ALFA))
      IF (A .GT. 172) GO TO 265
      ROC= ((QPC * V**2)/(2.0 * PI * 2.0 * ALFA * TK))
      C*EXP(A)*((FKO+(ZETROC/R)*FK1)

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```

282.000      GO TO 300
283.000 265 WRITE (3,2) Y(I)
284.000      OUTPUT 'ROC IS NOT AVAILABLE AT THIS EXPONENTIAL'
285.000      2 FORMAT (F5.3)
286.000      GO TO 300
287.000 270 ROC = 9999.0
288.000 300 RETURN
289.000      END
290.000 C
291.000 C
292.000 C
293.000      SUBROUTINE N04 (ZETROC, FKO,FK1,YROC,V,ALFA,R)
294.000      R=SQRT(ZETROC**2.0+YROC**2.0)
295.000      X=(V*R)/(2.0*ALFA)
296.000      IF(X, LE ,2.0) GO TO 110
297.000      IF(X, GT ,2.0) GO TO 120
298.000 110 T=X/3.75
299.000      X=X/2.0
300.000      FID=1.0+3.515623*T**2+3.0899424*T**4+1.2067492*T**6
301.000      C      +0.2659732*T**8+0.0360768*T**10+0.0045813*T**12
302.000      FKO=-ALDG(X)*FID-0.57721566+0.4227842*X**2+0.23069756*X**4+
303.000      C      0.0348859*X**6+0.00262698*X**8+0.0001075*X**10+0.0000074*X**12
304.000      FII=X*(0.5 + 0.87890594 *T**2 + 0.51498869 *T**4
305.000      C      +0.15084934 *T**6 + 0.02658733 *T**8
306.000      C      +0.00301532 *T**10 + 0.00032411 *T**12 )
307.000      FK1=(1.0/(2.0*X))*(2.0*X * ALDG(X) * FII + 1.0 + 0.15443144 *X**2
308.000      C      -0.67278579 *X**4 - 0.18156897 *X**6
309.000      C      -0.1919402 *X**8 - 0.00110404 *X**10
310.000      C      +0.00004686 *X**12)
311.000      RETURN
312.000 120 U=2.0/X
313.000      FKO=(EXP(-X)/SQRT(X)) * (1.25331414 - 0.07832358 * U
314.000      C      +0.02189568 * U**2 - 0.01062446 * U**3
315.000      C      +0.00587872 * U**4 - 0.0025154 * U**5
316.000      C      +0.00053208 * U**6 )
317.000      FK1=(EXP(-X)/SQRT(X)) * (1.25331414
318.000      C      +0.23498619 * U - 0.03655620 * U**2
319.000      C      +0.01504268 * U**3 - 0.00780353 * U**4
320.000      C      +0.0325614 * U**5 - 0.00068245 * U**6)
321.000      RETURN

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322.000      END
323.000      C
324.000      C
325.000      C
326.000      SUBROUTINE ROC2D
327.000      2D RATE OF COOLING DISTRIBUTION BY MOHAMED EL-SHAYER , 1980
328.000      DIMENSION TIME(100) , ZETA(100) , Y(20) , ROC(20,100)
329.000      EFF=0.85
330.000      PI=3.14159
331.000      TK=0.1
332.000      ALFA=0.065
333.000      S=4
334.000      OUTPUT ' '
335.000      OUTPUT 'NUMBER OF Y DIVISIONS (ANY NUMBER)?'
336.000      READ (2,1)NY
337.000      OUTPUT 'NUMBER OF ZETA DIVISIONS (ANY NUMBER)?'
338.000      READ (2,1)NZ
339.000      OUTPUT 'INCREMENT REQUIRED ON Y AXIS (CM)'
340.000      READ (2,1)YIR
341.000      OUTPUT 'TIME INCREMENT REQUIRED (SEC)?'
342.000      READ (2,1)TIR
343.000      OUTPUT 'PREHEAT TEMPERATURE (DEG C)?'
344.000      READ (2,1)TO
345.000      OUTPUT 'WELDING VOLTAGE (VOLTS)?'
346.000      READ (2,1)VT
347.000      OUTPUT 'WELDING CURRENT (AMPS)?'
348.000      READ (2,1)A
349.000      OUTPUT 'WELDING SPEED (IN/MIN)?'
350.000      READ (2,1)V
351.000      OUTPUT 'PLATE THICKNESS (IN)?'
352.000      READ (2,1)H
353.000      OUTPUT ' '
354.000      OUTPUT 'WELDING PARAMETERS:'
355.000      Q=VT*A*EFF
356.000      QPUT1=Q/H
357.000      QPUT2=Q/(H*2.54)
358.000      QPUA1=QPUT1/(V/60)
359.000      QPUA2=QPUT2/((V*2.54)/60)
360.000      QPUA3=QPUA2/100.0
361.000      QPUA4=QPUA1/1000.0

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362.000      QPUA5=QPUA2/1000.0
363.000      QPUA6=QPUA3/1000.0
364.000      H=H*2.54
365.000      V=(V*2.54)/60.0
366.000      QPC=QPUT2/4.1819
367.000      WRITE(3,2) TK
368.000      WRITE(3,3) ALFA
369.000      WRITE(3,4) TO
370.000      WRITE(3,5) H
371.000      WRITE(3,6) Q
372.000      WRITE (3,7) QPUT1
373.000      WRITE (3,8) QPUT2
374.000      WRITE (3,9) QPUA1
375.000      WRITE (3,10) QPUA2
376.000      WRITE (3,11) QPUA3
377.000      WRITE (3,12) QPUA4
378.000      WRITE (3,13) QPUA5
379.000      WRITE (3,14) QPUA6
380.000      WRITE (3,15) QPC
381.000      WRITE (3,16) VT
382.000      WRITE (3,17) A
383.000      WRITE (3,18) V
384.000      WRITE (3,19) EFF
385.000      WRITE (3,20)
386.000      WRITE (3,21)
387.000      WRITE (3,22)
388.000      DO 90 I=1,NY
389.000      DO 90 J=1,NZ
390.000          90 ROC(I,J) = 0.0
391.000      DO 100 I=1,NY
392.000          100 Y(I)=YIR*(I-1)
393.000      WRITE (3,23) (Y(I),I=1,NY)
394.000      DO 300 J=1,NZ
395.000          TIME(J)=-TIR*S
396.000      ZETA(J)=-V*TIME(J)
397.000      DO 200 I=1,NY
398.000          IF((ZETA(J)+Y(I)).EQ.0.0)GO TO 140
399.000      R=SQRT(ZETA(J)**2.0+Y(I)**2.0)
400.000      X=(Q*R)/(2.0*ALFA)
401.000      IF(X. LE .2.0) GO TO 110

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402.000 IF(X, GT, 2.0) GO TO 120
403.000 110 T=X/3.75
404.000 X=X/2.0
405.000 FIO=1.0+3.515623*T**2+3.0899424*T**4+1.2067492*T**6
406.000 C +0.2659732*T**8+0.0360768*T**10+0.0045813*T**12
407.000 FKO=-ALOG(X)*FIO-0.57721566+0.4227842*X**2+0.23069756*X**4+
408.000 C 0.0348859*X**6+0.00262698*X**8+0.0001075*X**10+0.0000074*X**12
409.000 FII=X*(0.5 + 0.87890594 *T**2 + 0.51498869 *T**4
410.000 C +0.15084934 *T**6 + 0.02658733 *T**8
411.000 C +0.00301532 *T**10 + 0.00032411 *T**12 )
412.000 FK1=(1.0/(2.0*X))*(2.0*X * ALOG(X) * FII + 1.0 + 0.15443144 *X**2
413.000 C -0.67278579 *X**4 - 0.18156897 *X**6
414.000 C -0.1919402 *X**8 - 0.00110404 *X**10
415.000 C -0.00004686 *X**12)
416.000 GO TO 130
417.000 120 U=2.0/X
418.000 FKO=(EXP(-X)/SQRT(X)) * (1.25331414 - 0.07832358 * U
419.000 C +0.02189548 * U**2 - 0.01062446 * U**3
420.000 C +0.00587872 * U**4 - 0.0025154 * U**5
421.000 C +0.00053208 * U**6 )
422.000 FK1=(EXP(-X)/SQRT(X)) * (1.25331414
423.000 C +0.23498619 * U - 0.03655620 * U**2
424.000 C +0.01504268 * U**3 - 0.00780353 * U**4
425.000 C +0.0325614 * U**5 - 0.00068245 * U**6)
426.000 130 RDC(I,J)=((QFC * V**2)/(2.0 * FI * 2.0 * ALFA * TK))
427.000 C * EXP(-V * ZETA(J)/(2.0 * ALFA)) * (FK0 +
428.000 C (ZETA(J)/R) * FK1)
429.000 GO TO 200
430.000 140 RDC(I,J)=100
431.000 200 CONTINUE
432.000 S=S-1
433.000 300 CONTINUE
434.000 DO 400 J=1,NZ
435.000 WRITE(3,24) TIME(J), ZETA(J), (RDC(I,J), I=1,NY)
436.000 400 CONTINUE
437.000 1 FORMAT (1G)
438.000 2 FORMAT (/, 'THERMAL CONDUCTIVITY TK=',F5.3, ' CAL/CM-S-DC')
439.000 3 FORMAT (/, 'THERMAL DIFFUSIVITY ALFA=',F5.3, ' CM**2/S')
440.000 4 FORMAT (/, 'PREHEAT TEMPERATURE TO=',F6.1, ' DEG C')
441.000 5 FORMAT (/, 'PLATE THICKNESS H=',F5.2, ' CM')

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442.000 6 FORMAT ('WELDING POWER(EFFECTIVE) Q=',F10.1,' J/S')
443.000 7 FORMAT ('HEAT INPUT PER UNIT THICKNESS QPUT1=',F10.1,' J/S-IN')
444.000 8 FORMAT ('HEAT INPUT PER UNIT THICKNESS QPUT2=',F10.1,' J/S-CM')
445.000 9 FORMAT ('HEAT INPUT PER UNIT AREA QPUA1=',F15.1,' J/IN*2')
446.000 10 FORMAT ('HEAT INPUT PER UNIT AREA QPUA2=',F15.1,' J/CM*2')
447.000 11 FORMAT ('HEAT INPUT PER UNIT AREA QPUA3=',F15.1,' J/MM*2')
448.000 12 FORMAT ('HEAT INPUT PER UNIT AREA QPUA4=',F10.1,' KJ/IN*2')
449.000 13 FORMAT ('HEAT INPUT PER UNIT AREA QPUA5=',F10.1,' KJ/CM*2')
450.000 14 FORMAT ('HEAT INPUT PER UNIT AREA QPUA6=',F10.2,' KJ/MM*2')
451.000 15 FORMAT ('HEAT INPUT PER CALORIES QPC=',F10.1,' CAL/S-CM')
452.000 16 FORMAT ('WELDING VOLTAGE VT=',F8.1,' VOLTS')
453.000 17 FORMAT ('WELDING CURRENT A=',F8.3,' AMPS')
454.000 18 FORMAT ('WELDING SPEED V=',F6.3,' CM/S')
455.000 19 FORMAT ('WELDING EFFECIENCY EFF=',F4.2,/)
456.000 20 FORMAT ('15X,COMPUTED RATE OF COOLING ROC(ZETA,Y)')
457.000 21 FORMAT ('25X,DEGREES CELSIUS')
458.000 22 FORMAT ('/,TIME (SEC)',4X,'ZETA (CM)',20X,'Y (CM)')
459.000 23 FORMAT ('/,24X,8F6.3,/)
460.000 24 FORMAT ('1X,F8.2,3X,F8.2,4X,8F6.0,/)
461.000 RETURN
462.000 END
463.000 C
464.000 C
465.000 C
466.000 SUBROUTINE RWCL2D
467.000 2D RATE OF COOLING AT WELD CENTRE LINE BY MOHAMED EL-SHAYER , 1980
468.000 DIMENSION TIME(100) , ZETA(100) , T(100) , ROC(100)
469.000 EFF=0.85
470.000 PI=3.14159
471.000 TK=0.1
472.000 ALFA=0.065
473.000 S=4
474.000 OUTPUT ' , '
475.000 OUTPUT 'NUMBER OF ZETA DIVISIONS (ANY NUMBER)?'
476.000 READ (2,1)NZ
477.000 OUTPUT 'TIME INCREMENT REQUIRED (SEC)?'
478.000 READ (2,1)TIR
479.000 OUTPUT 'PREHEAT TEMPERATURE (DEG C)?'
480.000 READ (2,1)TO
481.000 OUTPUT 'WELDING VOLTAGE (VOLTS)?'

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482.000      READ (2,1)VT
483.000      OUTPUT 'WELDING CURRENT (AMPS)?'
484.000      READ (2,1)A
485.000      OUTPUT 'WELDING SPEED (IN/MIN)?'
486.000      READ (2,1)V
487.000      OUTPUT 'PLATE THICKNESS (IN)?'
488.000      READ (2,1)H
489.000      OUTPUT 'TEMPERATURE (DEG C)?'
490.000      READ (2,1)(T(J),J=1,NZ)
491.000      OUTPUT ' '
492.000      OUTPUT 'WELDING PARAMETERS:'
493.000      Q=VT*A*EFF
494.000      QFUT1=Q/H
495.000      QFUT2=Q/(H*2.54)
496.000      QPUA1=QFUT1/(V/60)
497.000      QPUA2=QFUT2/((V*2.54)/60)
498.000      QPUA3=QPUA2/100.0
499.000      QPUA4=QPUA1/1000.0
500.000      QPUA5=QPUA2/1000.0
501.000      QPUA6=QPUA3/1000.0
502.000      H=H*2.54
503.000      V=(V*2.54)/60.0
504.000      QPC=QFUT2/4.1819
505.000      WRITE(3,2) TK
506.000      WRITE(3,3) ALFA
507.000      WRITE(3,4) TO
508.000      WRITE(3,5) H
509.000      WRITE(3,6) R
510.000      WRITE (3,7) QFUT1
511.000      WRITE (3,8) QFUT2
512.000      WRITE (3,9) QPUA1
513.000      WRITE (3,10) QPUA2
514.000      WRITE (3,11) QPUA3
515.000      WRITE (3,12) QPUA4
516.000      WRITE (3,13) QPUA5
517.000      WRITE (3,14) QPUA6
518.000      WRITE (3,15) QPC
519.000      WRITE (3,16) VT
520.000      WRITE (3,17) A
521.000      WRITE (3,18) V

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522.000      WRITE (3,19) EFF
523.000      WRITE (3,20)
524.000      WRITE (3,21)
525.000      WRITE (3,22)
526.000      DO 300 J=1,NZ
527.000      TIME(J)=-TIR*S
528.000      ZETA(J)=-V*TIME(J)
529.000      ROC(J) =- 2.0 * PI * (TN**2/ALFA) * (4*V)/QFC)**2*(T(J)-TO)**3
530.000      S=S-1
531.000      300 CONTINUE
532.000      DO 400 J=1,NZ
533.000      WRITE(3,23) TIME(J), ZETA(J), ROC(J)
534.000      400 CONTINUE
535.000      1 FORMAT (13G)
536.000      2 FORMAT (/,'THERMAL CONDUCTIVITY TN=',F5.3,' CAL/CM-S-OC')
537.000      3 FORMAT (' THERMAL DIFFUSIVITY ALFA=',F5.3,' CM**2/S')
538.000      4 FORMAT ('PREHEAT TEMPERATURE TO=',F6.1,' DEG C')
539.000      5 FORMAT ('PLATE THICKNESS H=',F5.2,' CM')
540.000      6 FORMAT ('WELDING POWER(EFFECTIVE) Q=',F10.1,' J/S')
541.000      7 FORMAT ('HEAT INPUT PER UNIT THICKNESS QPUT1=',F10.1,' J/S-IN')
542.000      8 FORMAT ('HEAT INPUT PER UNIT THICKNESS QPUT2=',F10.1,' J/S-CM')
543.000      9 FORMAT ('HEAT INPUT PER UNIT AREA QPUA1=',F15.1,' J/IN**2')
544.000      10 FORMAT ('HEAT INPUT PER UNIT AREA QPUA2=',F15.1,' J/CM**2')
545.000      11 FORMAT ('HEAT INPUT PER UNIT AREA QPUA3=',F15.1,' J/MM**2')
546.000      12 FORMAT ('HEAT INPUT PER UNIT AREA QPUA4=',F10.1,' NJ/IN**2')
547.000      13 FORMAT ('HEAT INPUT PER UNIT AREA QPUA5=',F10.1,' NJ/CM**2')
548.000      14 FORMAT ('HEAT INPUT PER UNIT AREA QPUA6=',F10.2,' NJ/MM**2')
549.000      15 FORMAT ('HEAT INPUT PER CALORIES QFC=',F10.1,' CAL/S-CM')
550.000      16 FORMAT ('WELDING VOLTAGE VT=',F8.1,' VOLTS')
551.000      17 FORMAT ('WELDING CURRENT A=',F8.3,' AMPS')
552.000      18 FORMAT ('WELDING SPEED V=',F6.3,' CM/S')
553.000      19 FORMAT ('WELDING EFFECIENCY EFF=',F4.2,/)
554.000      20 FORMAT (15X,'COMPUTED RATE OF COOLING ROC(ZETA,Y)')
555.000      21 FORMAT (25X,'DEGREES CELSIUS')
556.000      22 FORMAT (/,'TIME (SEC)',4X,'ZETA (CM)',4X,'Y (CM)')
557.000      23 FORMAT (1X,F8.2,3X,F8.2,4X,F12.0,/)
558.000      RETURN
559.000      END
560.000 C
561.000 C

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562.000 C      SUBROUTINE TD3D
563.000 C
564.000 C      3D TEMPERATURE DISTRIBUTION AND ROC AT 704 BY MOHAMED EL-SHAYER , 1980
565.000 C      DIMENSION TIME(100) , ZETA(100) , R(20) , TEMP(20,100)
566.000 C      EFF=0.85
567.000 C      PI=3.14159
568.000 C      TK=0.1
569.000 C      ALFA=0.065
570.000 C      S=4
571.000 C      OUTPUT , ,
572.000 C      OUTPUT 'NUMBER OF Y DIVISONS (ANY NUMBER)?'
573.000 C      READ (2,1)NR
574.000 C      OUTPUT 'NUMBER OF ZETA DIVISONS (ANY NUMBER)?'
575.000 C      READ (2,1)NZ
576.000 C      OUTPUT 'INCREMENT REQUIRED ON Y AXIS (CM)'
577.000 C      READ (2,1)RIR
578.000 C      OUTPUT 'TIME INCREMENT REQUIRED (SEC)?'
579.000 C      READ (2,1)TIR
580.000 C      OUTPUT 'PREHEAT TEMPERATURE (DEG C)?'
581.000 C      READ (2,1)TO
582.000 C      OUTPUT 'WELDING VOLTAGE (VOLTS)?'
583.000 C      READ (2,1)VT
584.000 C      OUTPUT 'WELDING CURRENT (AMPS)?'
585.000 C      READ (2,1)A
586.000 C      OUTPUT 'WELDING SPEED (IN/MIN)?'
587.000 C      READ (2,1)V
588.000 C      OUTPUT , ,
589.000 C      OUTPUT 'WELDING PARAMETERS:'
590.000 C      Q=VT*A*EFF
591.000 C      QPUL1=Q/(V/60)
592.000 C      QPUL2=Q/((V*2.54)/60)
593.000 C      QPUL3=QPUL2/10.0
594.000 C      QPUL4=QPUL1/1000.0
595.000 C      QPUL5=QPUL2/1000.0
596.000 C      QPUL6=QPUL3/1000.0
597.000 C      V=(V*2.54)/60.0
598.000 C      QPC=Q/4.1819
599.000 C      WRITE(3,2) TK
600.000 C      WRITE(3,3) ALFA
601.000 C      WRITE(3,4) TO

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602.000      WRITE(3,6) R
603.000      WRITE (3,9)  QFUL1
604.000      WRITE (3,10) QFUL2
605.000      WRITE (3,11) QFUL3
606.000      WRITE (3,12) QFUL4
607.000      WRITE (3,13) QFUL5
608.000      WRITE (3,14) QFUL6
609.000      WRITE (3,15) QPC
610.000      WRITE (3,16) VT
611.000      WRITE (3,17) A
612.000      WRITE (3,18) V
613.000      WRITE (3,19) EFF
614.000      WRITE (3,20)
615.000      WRITE (3,21)
616.000      WRITE (3,22)
617.000      DO 50 I=1,NR
618.000      DO 50 J=1,NZ
619.000      50 TEMP(I,J) = 0.0
620.000      DO 100 I=1,NR
621.000      100 R(I)=RIR*(I-1)
622.000      WRITE(3,23) (R(I),I=1,NR)
623.000      DO 250 J=1,NZ
624.000      TIME(J)=-TIR*S
625.000      ZETA(J)=-V*TIME(J)
626.000      DO 200 I=1,NR
627.000      U=SQRT(ZETA(J)**2 + R(I)**2)
628.000      IF (U.EQ. 0.0)GO TO 150
629.000      F = (2.0 * PI * U * TK)
630.000      D=QPC/F
631.000      H = -V * (ZETA(J) + U) / (2.0 * ALFA)
632.000      TEMP(I,J)=TO+D*EXP(H)
633.000      GO TO 200
634.000      150 TEMP(I,J) = 99999.0
635.000      200 CONTINUE
636.000      S=S-1
637.000      250 CONTINUE
638.000      DO 300 J=1,NZ
639.000      WRITE(3,24) TIME(J), ZETA(J), (TEMP(I,J), I=1,NR)
640.000      300 CONTINUE
641.000      WRITE (3,25)

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642.000      OUTPUT 'ENTER MAXIMUM NUMBER OF ITERATION'
643.000      OUTPUT 'ENTER MAXIMUM NUMBER OF ITERATION'
644.000      READ(2,1) ITER
645.000      WRITE (3,26)
646.000      WRITE (3,27)
647.000      DO 500 I=1,NR
648.000      DO 350 J=1,NZ
649.000      JJ=NZ-J+1
650.000      IF (TEMP(I,JJ).GE.704.0) GO TO 400
651.000      350 CONTINUE
652.000      GO TO 450
653.000      400 IF(TEMP(I,JJ).EQ.704.0) GO TO 460
654.000      IF (JJ.EQ. NZ) GO TO 450
655.000      460 CALL RATEOC (I,JJ,ZETA,TIME,TK,QPC,V,ALFA,IO,R,RDC,
656.000      C
657.000      WRITE (3,28) RRQC,TIMROC,ZETROC,ROC
658.000      GO TO 500
659.000      450 WRITE (3,29) R(I)
660.000      OUTPUT 'NOT AVAILABLE AT THAT RADIUS'
661.000      500 CONTINUE
662.000      1 FORMAT (1G)
663.000      2 FORMAT (/, 'THERMAL CONDUCTIVITY TK=',F5.3, ' CAL/CM-S-OC')
664.000      3 FORMAT ( ' THERMAL DIFFUSIVITY ALFA=',F5.3, ' CM**2/S')
665.000      4 FORMAT ( 'PREHEAT TEMPERATURE TO=',F6.1, ' DEG C')
666.000      6 FORMAT ( 'WELDING POWER(EFFECTIVE) Q=',F10.1, ' J/S')
667.000      9 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL1=',F15.1, ' J/IN')
668.000      10 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL2=',F15.1, ' J/CM')
669.000      11 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL3=',F15.1, ' J/MM')
670.000      12 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL4=',F10.1, ' NJ/IN')
671.000      13 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL5=',F10.1, ' NJ/CM')
672.000      14 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL6=',F10.2, ' NJ/MM')
673.000      15 FORMAT ( 'HEAT INPUT PER CALORIES QPC=',F10.1, ' CAL/S')
674.000      16 FORMAT ( 'WELDING VOLTAGE VT=',F8.1, ' VOLTS')
675.000      17 FORMAT ( 'WELDING CURRENT A=',F8.3, ' AMPS')
676.000      18 FORMAT ( 'WELDING SPEED V=',F6.3, ' CM/S')
677.000      19 FORMAT ( 'WELDING EFFICIENCY EFF=',F4.2, '/')
678.000      20 FORMAT (15X, 'COMPUTED TEMPERATURE DISTRIBUTION T(ZETA,R)')
679.000      21 FORMAT (25X, 'DEGREES CELSIUS')
680.000      22 FORMAT (/, 'TIME (SEC)',4X, 'ZETA (CM)',20X, 'R (CM)')
681.000      23 FORMAT (/,24X,8F6.3,/)

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682.000      24 FORMAT (1X,F8.2,3X,F8.2,4X,8F6.0,/)
683.000      25 FORMAT (X,70(' '))
684.000      26 FORMAT (10X,' RATE OF COOLING AT TEMP =704 DEG C')
685.000      27 FORMAT (/,'R (CM)',5X,'TIME (SEC)',3X,'ZETA (CM)',8X,'ROC DEG C')
686.000      28 FORMAT (F6.3,4X,F7.2,6X,F7.2,8X,F12.0)
687.000      29 FORMAT (F9.3)
688.000      RETURN
689.000      END
690.000 C
691.000 C
692.000 C
693.000      SUBROUTINE RATEOC (I,JJ,ZETA,TIME,TK,QPC,V,ALFA,TO,R,
694.000      ROC,RROC,TIMROC,ZETROC,ITER)
695.000      DIMENSION TIME(100) , ZETA(100) , R(20)
696.000      T1=TIME (JJ)
697.000      T2=TIME (JJ+1)
698.000      PI=3.14159
699.000      RROC=R(I)
700.000      COUNT = 0.0
701.000      U1=SQRT(ZETA(JJ)**2 + R(I)**2)
702.000      IF (U1 .EQ. 0.0) GO TO 270
703.000      F=(2.0*PI*U1*TK)
704.000      D=QPC/F
705.000      H=-V*(ZETA(JJ) + U1) / (2.0*ALFA)
706.000      TEMP1 = TO + D*EXP(H) - 704
707.000      TIMROC = (T1+T2) / 2.0
708.000      ZETROC = -V*TIMROC
709.000      U = SQRT(ZETROC**2 + R(I)**2)
710.000      F = (2.0*PI*U*TK)
711.000      D = QPC / F
712.000      H = -V*(ZETROC + U) / (2.0*ALFA)
713.000      TEMROC = TO + D*EXP(H) - 704.0
714.000      TEMMID = TEMROC
715.000      TT = TEMP1 * TEMMID
716.000      IF (TT) 220 , 260 , 240
717.000      T2 = TIMROC
718.000      GO TO 250
719.000      240 TEMP1 = TEMMID
720.000      T1 = TIMROC
721.000      250 TCHECK = T2-T1

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722.000      COUNT = COUNT + 1
723.000      IF (ABS (TCHECK) .LE. 0.0001) .OR. COUNT .GT. ITER GO TO 260
724.000      GO TO 210
725.000      U = SQRT(ZETROC ** 2 + R(I) ** 2)
726.000      G = EXP ((-V / (2.0*ALFA)) * (U + ZETROC))
727.000      IF (U .EQ. 0.0) GO TO 270
728.000      A = 4.0 * PI * TK * ALFA * U
729.000      B = (QPC * V ** 2) / A
730.000      D = 1.0 + ZETROC / U
731.000      E = V * U ** 2.0
732.000      F = ZETROC * 2.0 * ALFA / E
733.000      ROC = B * (D + F) * G
734.000      RETURN
735.000      END
736.000
737.000
738.000
739.000
740.000      SUBROUTINE ROC3D
741.000      3D RATE OF COOLING DISTRIBUTION BY MOHAMED EL-SHAYER , 1980
742.000      DIMENSION TIME(100) , ZETA(100) , R(20) , ROC(20,100)
743.000      EFF=0.85
744.000      PI=3.14159
745.000      TK=0.1
746.000      ALFA=0.065
747.000      S=4
748.000      OUTPUT ' , '
749.000      OUTPUT 'NUMBER OF Y DIVISIONS (ANY NUMBER)?'
750.000      READ (2,1)NR
751.000      OUTPUT 'NUMBER OF ZETA DIVISIONS (ANY NUMBER)?'
752.000      READ (2,1)NZ
753.000      OUTPUT 'INCREMENT REQUIRED ON Y AXIS (CM)'
754.000      READ (2,1)RIR
755.000      OUTPUT 'TIME INCREMENT REQUIRED (SEC)?'
756.000      READ (2,1)TIR
757.000      OUTPUT 'PREHEAT TEMPERATURE (DEG C)?'
758.000      READ (2,1)TO
759.000      OUTPUT 'WELDING VOLTAGE (VOLTS)?'
760.000      READ (2,1)VT
761.000      OUTPUT 'WELDING CURRENT (AMPS)?'
762.000      READ (2,1)A

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762.000      OUTPUT 'WELDING SPEED (IN/MIN)'
763.000      READ (2,1) V
764.000      OUTPUT '
765.000      OUTPUT 'WELDING PARAMETERS:
766.000      Q=VT*AX*EFF
767.000      QPUL1=Q/(V/60)
768.000      QPUL2=Q/((V*2.54)/60)
769.000      QPUL3=QPUL2/10.0
770.000      QPUL4=QPUL1/1000.0
771.000      QPUL5=QPUL2/1000.0
772.000      QPUL6=QPUL3/1000.0
773.000      V=(V*2.54)/60.0
774.000      QPC=Q/4.1819
775.000      WRITE(3,2) TK
776.000      WRITE(3,3) ALFA
777.000      WRITE(3,4) TO
778.000      WRITE(3,6) Q
779.000      WRITE(3,9) QPUL1
780.000      WRITE(3,10) QPUL2
781.000      WRITE(3,11) QPUL3
782.000      WRITE(3,12) QPUL4
783.000      WRITE(3,13) QPUL5
784.000      WRITE(3,14) QPUL6
785.000      WRITE(3,15) QPC
786.000      WRITE(3,16) VT
787.000      WRITE(3,17) A
788.000      WRITE(3,18) V
789.000      WRITE(3,19) EFF
790.000      WRITE(3,20)
791.000      WRITE(3,21)
792.000      WRITE(3,22)
793.000      DO 100 I=1,NR
794.000      100 R(I)=RIR*(I-1)
795.000      WRITE(3,23) (R(I),I=1,NR)
796.000      DO 300 J=1,NZ
797.000      TIME(J)=-TIR*JS
798.000      ZETA(J)=-V*TIME(J)
799.000      DO 200 I=1,NR
800.000      G=EXP((-V/(2.0*ALFA))*(SQRT(ZETA(J)**2.0+R(I)**2.0)+ZETA(J)))
801.000      IF (( ZETA(J) + R(I)) .EQ. 0.0) GO TO.150

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802.000      A=4.0*PI*TK*ALFA*SQRT(ZETA(J)**2.0+R(I)**2.0)
803.000      B=(QFC*V**2.0)/A
804.000      D=1.0+ZETA(J)/SQRT(ZETA(J)**2.0 + R(I)**2.0)
805.000      E=V*(ZETA(J)**2.0+R(I)**2.0)
806.000      F=(ZETA(J)**2.0*ALFA)/E
807.000      ROC(I,J)=B*(D+F)*G
808.000      GO TO 200
809.000      150 ROC(I,J) = 99999.0
810.000      200 CONTINUE
811.000      S=S-1
812.000      300 CONTINUE
813.000      DO 400 J=1,NZ
814.000      WRITE(3,24) TIME(J), ZETA(J), (ROC(I,J), I=1,NR)
815.000      400 CONTINUE
816.000      1 FORMAT (1G)
817.000      2 FORMAT (/, 'THERMAL CONDUCTIVITY TK=',F5.3, ' CAL/CM-S-OC')
818.000      3 FORMAT ( ' THERMAL DIFFUSIVITY ALFA=',F5.3, ' CM**2/S')
819.000      4 FORMAT ( 'PREHEAT TEMPERATURE TO=',F6.1, ' DEG C')
820.000      6 FORMAT ( 'WELDING POWER(EFFECTIVE) Q=',F10.1, ' J/S')
821.000      9 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QPUL1=',F15.1, ' J/IN')
822.000      10 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QPUL2=',F15.1, ' J/CM')
823.000      11 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QPUL3=',F15.1, ' J/MM')
824.000      12 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QPUL4=',F10.1, ' NJ/IN')
825.000      13 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QPUL5=',F10.1, ' NJ/CM')
826.000      14 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QPUL6=',F10.2, ' NJ/MM')
827.000      15 FORMAT ( 'HEAT INPUT PER CALORIES QFC=',F10.1, ' CAL/S')
828.000      16 FORMAT ( 'WELDING VOLTAGE VT=',F8.1, ' VOLTS')
829.000      17 FORMAT ( 'WELDING CURRENT A=',F8.3, ' AMPS')
830.000      18 FORMAT ( 'WELDING SPEED V=',F6.3, ' CM/S')
831.000      19 FORMAT ( 'WELDING EFFECIENCY EFF=',F4.2,/)
832.000      20 FORMAT (15X, 'COMPUTED ROC DISTRIBUTION ROC(ZETA,R)')
833.000      21 FORMAT (25X, 'DEGREES CELSIUS')
834.000      22 FORMAT (/, 'TIME (SEC)',4X, 'ZETA (CM)',20X, 'R (CM)')
835.000      23 FORMAT (/,24X,8F6.3,/)
836.000      24 FORMAT (1X,F8.2,3X,F8.2,4X,8F6.0,/)
837.000      RETURN
838.000      END
839.000 C
840.000 C
841.000 C
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842.000 SUBROUTINE RWCL3D
843.000 C 3D ROC AT WELD CENTRE LINE BY MOHAMED EL-SHAYER , 1980
844.000 DIMENSION TIME(100) , ZETA(100) , T(20) , ROC(100)
845.000 EFF=0.85
846.000 PI=3.14159
847.000 TK=0.1
848.000 ALFA=0.065
849.000 S=4
850.000 OUTPUT ' '
851.000 OUTPUT 'NUMBER OF Y DIVISIONS (ANY NUMBER)?'
852.000 READ (2,1)NR
853.000 OUTPUT 'NUMBER OF ZETA DIVISIONS (ANY NUMBER)?'
854.000 READ (2,1)NZ
855.000 OUTPUT 'INCREMENT REQUIRED ON Y AXIS (CM)'
856.000 READ (2,1)RIR
857.000 OUTPUT 'TIME INCREMENT REQUIRED (SEC)?'
858.000 READ (2,1)TIR
859.000 OUTPUT 'PREHEAT TEMPERATURE (DEG C)?'
860.000 READ (2,1)TO
861.000 OUTPUT 'WELDING VOLTAGE (VOLTS)?'
862.000 READ (2,1)VT
863.000 OUTPUT 'WELDING CURRENT (AMPS)?'
864.000 READ (2,1)A
865.000 OUTPUT 'WELDING SPEED (IN/MIN)?'
866.000 READ (2,1)V
867.000 OUTPUT 'TEMPERATURE (DEG C) ?'
868.000 READ (2,1)(T(J),J=1,NZ)
869.000 OUTPUT ' '
870.000 OUTPUT 'WELDING PARAMETERS:'
871.000 Q=VT*ALFA*EFF
872.000 QPUL1=Q/(V/60)
873.000 QPUL2=Q/((V*2.54)/60)
874.000 QPUL3=QPUL2/10.0
875.000 QPUL4=QPUL1/1000.0
876.000 QPUL5=QPUL2/1000.0
877.000 QPUL6=QPUL3/1000.0
878.000 V=(V*2.54)/60.0
879.000 QPC=Q/4.1819
880.000 WRITE(3,2) TK
881.000 WRITE(3,3) ALFA

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882.000 WRITE(3,4) TO
883.000 WRITE(3,6) Q
884.000 WRITE(3,9) QFUL1
885.000 WRITE(3,10) QFUL2
886.000 WRITE(3,11) QFUL3
887.000 WRITE(3,12) QFUL4
888.000 WRITE(3,13) QFUL5
889.000 WRITE(3,14) QFUL6
890.000 WRITE(3,15) QFC
891.000 WRITE(3,16) VT
892.000 WRITE(3,17) A
893.000 WRITE(3,18) V
894.000 WRITE(3,19) EFF
895.000 WRITE(3,20)
896.000 WRITE(3,21)
897.000 WRITE(3,22)
898.000 DO 300 J=1,NZ
899.000 TIME(J)=-TIR#S
900.000 ZETA(J)=V*TIME(J)
901.000 ROC(J) = (-2.0 * PI * TK * V* (T(J) - TO) ** 2.0)/QPC
902.000 S=S-1
903.000 300 CONTINUE
904.000 DO 400 J=1,NZ
905.000 WRITE(3,23) TIME(J), ZETA(J), ROC(J)
906.000 400 CONTINUE
907.000 1 FORMAT (13G)
908.000 2 FORMAT (/, ' THERMAL CONDUCTIVITY TK=',F5.3, ' CAL/CM-S-OC')
909.000 3 FORMAT ( ' THERMAL DIFFUSIVITY ALFA=',F5.3, ' CM**2/S')
910.000 4 FORMAT ( 'PREHEAT TEMPERATURE TO=',F6.1, ' DEG C')
911.000 6 FORMAT ( 'WELDING POWER(EFFECTIVE) Q=',F10.1, ' J/S')
912.000 9 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL1=',F15.1, ' J/IN')
913.000 10 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL2=',F15.1, ' J/CM')
914.000 11 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL3=',F15.1, ' J/MM')
915.000 12 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL4=',F10.1, ' KJ/IN')
916.000 13 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL5=',F10.1, ' KJ/CM')
917.000 14 FORMAT ( 'HEAT INPUT PER UNIT LENGTH QFUL6=',F10.2, ' KJ/MM')
918.000 15 FORMAT ( 'HEAT INPUT PER CALORIES QFC=',F10.1, ' CAL/S')
919.000 16 FORMAT ( 'WELDING VOLTAGE VT=',F8.1, ' VOLTS')
920.000 17 FORMAT ( 'WELDING CURRENT A=',F8.3, ' AMPS')
921.000 18 FORMAT ( 'WELDING SPEED V=',F6.3, ' CM/S')

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922.000 19 FORMAT ('WELDING EFFECIENCY EFF=',F4.2,/)
923.000 20 FORMAT (15X,'COMPUTED' ROC AT WELD CENTRE LINE ROC(ZETA,R)')
924.000 21 FORMAT (25X,'DEGREES CELSIUS')
925.000 22 FORMAT (/, 'TIME (SEC)',4X,'ZETA (CM)',4X,'R (CM)')
926.000 23 FORMAT (1X,F6.2,3X,F6.2,4X,F12.0,/)
927.000 RETURN
928.000 END

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END

3	1	H	0	8	H	8	2	1
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FIN